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THE PHYSICAL PROPERTIES

OF

STRUCTURAL AND ALLOY STEELS

by

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This Thesis is respectfully submitted to the Graduate Board of Lehigh University in partial fulfillment of the requirements for the degree of Master of Science.

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Head of the Department of Civil Engineering

Date ______________

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I. INTRODUCTION

1. Scope - A recent investigation of web buckling in steel beams carried out in the Fritz Engineering Laboratory, Lehigh University, showed that the ratio between the yield-point stress in shear and the yield-point stress in tension varied considerably for different grades of structural steel. In order to corroborate this finding, an extensive investigation was conducted on a number of grades of structural and alloy steels. The structural steel was tested in the condition in which it came from the mill, except for a few specimens which were annealed before being tested. The alloy steels were tested in both annealed and heat-treated conditions.

This investigation also included the determination of Poisson's Ratio because of its relationship with the tensile and shearing properties of the steel.

The other physical properties investigated were as follows: the shearing modulus of elasticity and the ultimate strength in shear, the tensile modulus of elasticity and the ultimate strength in tension. The hardness and ductility of some of the steels were also determined.

2. Program - In order to measure the deformations of the specimens while they were under stress, special instruments had to be designed. The instruments included an apparatus for measuring the strains in a torsion specimen.

An apparatus was also needed to measure the lateral deformation of a specimen under tensile stress so that Poisson's ratio could be computed.

The structural steel used in this investigation included material from rolled structural sections and plates. As the use of alloy steels is becoming more prevalent in present day design, a composite group of alloy steels were tested in order that their physical properties could be studied.

The results of this investigation are analyzed and compared with results obtained by other investigators.

3. Acknowledgment - All experiments were conducted in the Fritz Engineering Laboratory, except the hardness tests which were made at the Metallurgical Laboratory of the University. Acknowledgment is made to Inge Lyse, Research Assistant Professor of Engineering Materials, for his interest shown and suggestions made during the investigation. Acknowledgment is also made to the other members of the research staff of the Fritz Engineering Laboratory.

The Bethlehem Steel Company, Bethlehem, Pennsylvania, supplied all the material for this investigation with the exception of one alloy steel which was furnished by the Lukens Steel Company, Coatesville, Pennsylvania.

II. MATERIALS AND TEST SPECIMENS

1. Structural Steel - The structural steel used in this investigation consisted of material taken from rolled plates, bars, and I-beams. This steel had considerable range in its yield-point strength and a corresponding variation in its ductility. The material was tested in the same condition as received from the mill except in a few cases in which it was annealed before testing.

The material from rolled plates and I-beams, was, in most cases, too thin to permit a satisfactory test on round torsion specimens. As a substitute for a torsion test, slotted plate specimens were made. A sketch of a slotted plate specimen is shown in Fig. 1. These shear specimens were made very carefully so that bending stresses were reduced to a minimum. It is to be noted that the section under shearing stress is about 1/2-in. long. This length was decided upon as it proved to be more satisfactory than did other lengths. Fig. 2 is a photo-elastic picture of a slotted plate specimen. It is to be noted that this photo-elastic specimen is slightly different than the one used in this investigation. The shearing stresses produced however, are the same for both. This photo-elastic picture indicates a nearly even distribution of shearing stresses along the section. Additional stresses appear at the end of the cuts, but these should have little effect on the section under shearing stress.

The round torsion specimens were of various diameters, depending upon the thickness of the material used. In order to study the effect of size on the strength of a specimen, a few tensile and torsion specimens of various sizes were made from a 1-1/2 in. diameter rolled bar. These sizes ranged from 1/2 to 1-1/2 in. in diameter, the smaller specimens being made from the core of the rolled bar.

A study was also made on the yield-point strength in shear of solid and hollow torsion bars. Three grades of steel were used and all specimens were tested in an annealed condition.

The tensile specimens from plates and I-beams were tested as flat bars while all other structural steel specimens were circular in shape. Both lateral and longitudinal deformations were observed on the circular specimens.

2. Alloy Steel - A composite group of alloy steels in heat-treated and annealed conditions were included in this investigation. These steels included such alloys as nickel, chromium, vanadium, molybdenum, and tungsten. The chemical analysis and heat treatment of these steels can be seen in Table I. All the alloy steel specimens were 7/8-in. in diameter bars, both for tensile and torsion tests.

III. METHOD OF TESTING AND APPARATUS

1. Shearing Tests - Two methods of testing were used to determine the shearing properties of the structural steel, namely; torsion tests on solid and hollow bars, and shear tests on slotted plate specimens.

The torsion tests were made in an Olsen 24,000 lb-in. capacity torsion machine. The angular twist was measured by means of a specially constructed instrument which is shown in Fig. 3. This instrument consists of two steel collars, each of which is attached to the specimen by means of three screws. The two collars are held exactly three inches apart by a space-bar which is removed after the collars have been placed on the specimen. The relative rotation between the two collars is measured by an Ames dial graduated to 1/10,000-in. This dial is attached to one of the collars and the plunger of the dial is in contact with a smooth bearing surface connected to the other collar.

The torsion specimens were carefully centered in these two collars before being placed in the testing machine. The distance from the center of the specimen to the plunger on the dial was measured accurately and the deformation at the surface of the specimen calculated from the observed rotation of the collars.

In order to check the accuracy of this apparatus, a calibration test was made. A small mirror was attached to each of the collars. By means of a telescope and two scales the relative rotation between the two collars was measured. The results obtained by this method agreed very well with those obtained by the direct reading of the Ames dial. The difference between these two deformation curves was very small, as can be seen in Fig. 4.

In making the torsion tests the torque was first applied by hand and deformation readings taken at certain increments of loading. After a definite yield point had been reached, the instrument was removed and the torque applied by an electric motor until the specimen fractured.

As torsion tests could not be made satisfactorily on specimens made from thin plates, slotted plate specimens were substituted and these were tested in a tension machine. A slotted plate specimen with the Huggenberger extensometers attached is shown in Fig. 5. These Huggenberger extensometers are designed on the lever principle and are very sensitive instruments. They consist of a fixed knife edge at one end of the gage length and a movable knife edge at the other end. The movement of the knife edge is multiplied by a long lever arm and is further multiplied by a pointer. The movement of the pointer is observed on a graduated scale. A small mirror on the scale assists in observing the position of the pointer more accurately. The readings should be made from the position in which the pointer coincides with its reflection in the mirror.

As these Huggenberger extensometers were new and their multiplication factors seemed to be somewhat in error, several calibration tests were made. They were attached to a steel tensile specimen together with the Ewing extensometer, the calibration of which was known. Readings were taken on both instruments at several increments of loading and the results plotted. A typical calibration curve is shown in Fig. 6. From these tests an average multiplication ratio was computed for each instrument.

The Huggenberger extensometers were clamped to the slotted plate specimens so that the deformations could be measured over the 1/2-in. section that was under shearing stress. The gage length of these extensometers can be made either 1/2 in. or 1 in. by resetting the knife edges. With auxiliary parts, the gage length can be adjusted to almost any length desirable. The 1/2-in. gage length was used for these tests. As the multiplication ratios of the instruments are over 1000, strains of 20 millionths could easily be read. The high sensitivity proved very helpful in determining the yield-point stress of the material. Readings were made at several increments of loading up to the yield point at which the pointers of the extensometers moved very rapidly. After the yield point of the material had been reached, the instruments were removed from the specimen and the load was applied continuously until the specimen failed in shear.

2. Tensile Tests - The tensile tests of all the specimens were made in a 50,000-lb. capacity Riehle testing machine except in a few cases where it was necessary to use a 300,000-lb. Olsen testing machine. Two Huggenberger extensometers which had multiplication ratios of about 350 were used to measure the deformations on the flat structural steel specimens. These extensometers were designed on the same principle as those used on the slotted plate specimens, but they were not as sensitive. However, for a tensile test, they were accurate enough and proved to be very reliable. The yield point of these tensile bars was determined by the sudden movement of the extensometer pointers.

The Ewing Extensometer was used on all the circular structural and alloy steels for the determination of the tensile properties. This instrument, which is shown in Fig. 7, proved to be very accurate in determining the elastic properties of the steel. It consists of two yokes attached to the specimen by means of pointed screws. These yokes are set either at two or eight inches apart, by means of standard bars. After the extensometer has been attached to the specimen in the testing machine, the standard bar is removed so that the yokes are free to rotate. The yokes are connected together at the back by a member which projects from the lower yoke and is made in the form of a rounded point at the top. This rounded point is held in a recess in the top yoke by means of a spring, thus forming a fulcrum about which the top yoke rotates when an extension in the test piece takes place. Suspended from the top yoke in front, is another member. With such an arrangement of levers, the suspended rod in front will move twice as far as the extension of the specimen. In the lower end of this suspended rod is a small wire cross-hair, the movement of which is measured by means of the microscope. Inside the microscope is a scale graduated to 0.002 of an inch, and one tenth of each graduation may be estimated. The graduated scale is illuminated by the reflection of light from a mirror directly behind the cross-hair. The instrument can be easily set to a convenient zero and if it goes out of range, it can be brought back by means of an adjustment screw.

For the tensile tests, a speed of 0.05 in. per minute of the testing machine was used. However, when both the lateral and longitudinal deformations were taken at the same time, the load was applied slowly by hand in order to eliminate vibrations. After a definite yield point had been reached, all instruments were removed and a higher speed was used to apply the load until the specimen fractured. Before being tested, each tensile specimen was marked with small holes one inch apart along the length of the bar so that the amount of permanent elongation could be measured. The reduction in area of circular specimens was also used as a measure of ductility.

3. Poisson's Ratio Tests - An apparatus by which the lateral deformation of a bar under tensile stress could be measured was one of the important features of this investigation. Several different types of apparatus were designed, but only one of them proved to be satisfactory. This instrument is shown in Fig. 8. It is very simple in form, as it consists merely of a split circular collar made of spring steel. This collar is attached to the specimen by pointed screws placed diametrically through the collar. After the collar has been firmly set on the specimen, two Huggenberger Extensometers were placed across the opening in the collar so that the movement of this opening could be determined.

A calibration test was made on the Poisson's ratio apparatus to determine the relative movement between the point at which the screws were attached to the specimen and the point where the extensometers were placed across the gap in the collar. This calibration was made by clamping the apparatus in a small vice. With the use of two sets of Huggenberger Extensometers the movement at the screws and the movement at the gap could be measured directly and the relation between the two points computed. The multiplication ratio of the apparatus was found to be 2.16.

While measuring the lateral deformations the testing machine was operated by hand. Observations of the lateral and longitudinal deformations were made at several increments of loading up to the yield point of the material. When structural steel was tested, the yield point of the material could be detected very readily by both the lateral and longitudinal extensometers. As the alloy steels did not have a definite yield point, readings were made after the proportional limit was reached, and in some cases readings were made up toward the ultimate load.

4. Hardness Tests - A Brinell Hardness machine was used to determine the relative hardness of the alloy steels used in this investigation. To conduct this test the specimen was placed on the anvil of the hardness machine. A 5-mm hardened steel ball was attached to the piston of an oil ram

and pressed against the test specimen under a load of 750 kilograms. The diameter of the indentation was measured by a specially constructed microscope. The ratio of the load in kilograms to the surface area of the indentation is a basis for the Brinell hardness scale.

IV. EXPERIMENTAL DATA

The data is presented in Tables I to VIII and in Fig. 1 to 19 inclusive. Table I gives the chemical composition of the alloy steels used in the investigation. Table II presents the results made on solid and hollow torsion specimens. In Table III and IV are summarized the results of tests made on structural steel, and in Tables V and VI those of alloy steels. The results of earlier investigations on the yield point in shear and tension, and Poisson's Ratio of steel are given in Tables VII and VIII respectively.

In Fig. 1 is shown a diagram of a typical slotted plate specimen. Fig. 2 is a photo-elastic picture of a slotted plate specimen showing the stress distribution. The apparatus for measuring the torsional deformations and the calibration of the same apparatus are presented in Fig. 3 and 4 respectively. Fig. 5 shows a slotted plate specimen with the Huggenberger extensometers attached. The calibration of these extensometers is given in Fig. 6. The

Ewing extensometer is shown in Fig. 7, and the apparatus for measuring the lateral deformations in Fig. 8. Fig. 9 is a diagram showing the useful limit point. The results of tests on solid torsion bars and slotted plate specimens are given in Fig. 10. The effect of size of a specimen on the ductility of structural steel is shown in Fig. 11. The relation between the yield-point stresses of structural steel are presented in Fig. 12. Deformation curves of structural steel are given in Fig. 13 and 14, and Fig. 15 is a photograph of typical fractures of structural steels. The relation between the yield-point stresses in shear and in tension for alloy steels is given in Fig. 16, and typical stress-strain curves in Fig. 17. A photograph of tensile fractures of alloy steels is shown in Fig. 18, and the relation between the yield-point stress and ductility of alloy steels is presented in Fig. 19.

V. DISCUSSION OF DATA

1. The Useful Limit Point - The true elastic limit of a material is the proportional limit which is the greatest unit stress the material can resist without taking a permanent set. As this limit is not readily determined, a useful limit point was adopted for the purpose of comparing the elastic strengths of the materials used in this investigation, and this point will hereafter be referred to as the

yield-point stress. This limit point was arbitrarily chosen as the stress at which the rate of strain was twice as great as the rate of strain on the straight line portion of the curve. A diagram showing the useful limit point is given in Fig. 9. This method of comparing the strengths of the alloy steels was quite necessary as these metals had no definite yield point. The Committee of the American Society of Civil Engineers used this same criterion for elastic strength in their analysis of steel columns, and Johnson's apparent elastic limit represents a similar value.

2. <u>Effect of Shape of Shear Specimens.</u> (a) <u>Solid Torsion and Slotted Plate Specimens</u> - Since slotted plate specimens were used to determine the shearing properties of material from plates and I-beams of structural steel, it was necessary to relate the shearing values obtained from the slotted plate specimens with those obtained from solid torsion specimens. Comparative test results of both types of specimens made from the same material are shown in Fig.10. It is to be noted that the yield point as found on the slotted plate specimen, compares very well with that of the solid torsion specimen. The slotted plate specimens in general had a more definite yield point and gave more consistent results. It is also to be noted that the shearing modulus of elasticity as determined on the slotted plate specimens, is higher than that determined on the solid torsion bars.

The ultimate strength obtained on the solid torsion bars of structural steel was in many cases equal to and greater than the ultimate strength in tension of the same material. This high shearing stress is due to the fact that after the proportional limit is reached, the torsion formula for shearing stress no longer holds true, because the stress in the material does not vary directly as the distance from the center of the specimen. The unit shearing stress, as computed from the maximum twisting moment, is not equal to the ultimate shearing strength of the material, but is merely a value from which the maximum twisting moment of a cylindrical shaft can be found. However, the ultimate shearing stress obtained on the slotted plate specimens was, in general about 85 per cent of the ultimate tensile stress for structural steel. This value is probably very close to the true ultimate shearing stress.

(b) Solid and Hollow Torsion Specimens - Three grades of steel were used to determine the relation between the torsional strengths of solid and hollow specimens. All of these specimens were annealed so that any internal stresses caused by rolling would be eliminated. The results of these tests are presented in Table II. It is to be noted that the ratio between the shearing yield-point stresses of the hollow and solid torsion specimens is greater for the soft steel than for the medium and hard steels. This indicates that the true shearing yield-point stress can be determined more accurately by a solid torsion specimen for soft steel than for medium or hard steels. For solid torsion specimens the ratio between the ultimate shearing stress and the ultimate tensile stress remained about the same for all three grades of steel. This ratio is more than unity, but as previously stated, the value of the ultimate strength in shear as computed from a solid torsion specimen is not correct. The ultimate stresses obtained on the hollow torsion specimens are somewhat lower - but even these values are only approximately correct.

3. <u>The Effect of Size of Specimens</u> - In order to obtain some information as to the effect of size of a test specimen on the physical properties of structural steel, specimens of three different sizes were machined from a 1-1/2 in. diameter rolled structural steel bar. The sizes were 1/2, 1, and 1-1/2 in. diameters. The smallest size was made from the center of the rolled section. It was found that the size of the specimen had no effect on the elastic properties of the material, as the tensile and shearing modulus and Poisson's ratio were about the same for the three sizes. However, the strength of the smaller specimens was less than that of the larger ones. As the smaller specimens were taken from the core of the rolled sections, the difference in strength is probably due to the

effect of the rolling of the material rather than the size of the specimen. The material on the outside of the rolled bar would be subject to more rolling than the material in the core. The strengths of these specimens are given in Table III. The yield-point stresses of the 1/2, 1, and 1-1/2 in. diameter bars were 35,350, 36,400 amd 39,350 lb. per sq. in. respectively. It is to be noted, however, that the computed ultimate stress in torsion for the 1-in. diameter bar is less than that of the 1/2-in. diameter bar, which is contrary to the above statement. As it has been stated that the ultimate strength of a solid torsion specimen is not a true test of its ultimate shearing stress, these values are unimportant. The 1-1/2 in. diameter bar was too large to be tested to failure in the torsion machine available.

The ductility of the different size specimens was determined by measuring the percentage of elongation in two inches and also the reduction in the area. These two properties are shown in Fig. 11 for the specimens tested. The change in the percentage of elongation for the different sized specimens is not due to the effect of the material, but to the effect of the size. The larger the diameter, the greater is the elongation in a given length. The reduction in the area of the specimens was not greatly affected by the size of the specimen, but there is a tendency for this property to decrease with an increase in size.

4. Physical Properties of Structural Steel.

(a) Relative Strength - The results of the tensile and shearing tests of the structural steel specimens are presented in Table III. In general these values represent the average of four or more specimens of the same material. Occasionally only two specimens of a kind were tested. The results show that the shearing yield-point stresses of these structural steels varied from as low as 16,500 to 29,200 lb. per sq.in. The tensile yield-point strength varied from 26,900 to 51,300 lb. per sq.in. A steel containing nickel and chromium which was included in this group, had yield-point stresses in shear and in tension of 41,700 and 48,000 lb. per sq.in. respectively. The yield-point stress of the material from rolled I-beams was found to be over 37,000 lb. per sq.in. in tension and 22,000 lb. per sq.in. or greater in shear. The above values indicate a great variation in the physical properties of the structural steel included in this investigation.

The ratio between the yield-point stress in shear and that in tension is given in the last column of Table III. It is to be noted that there is considerable variation in the ratio for the materials tested, ranging between 0.50 and 0.70 except in three cases. The three exceptions were materials containing nickle and chromium. The relation between the yield points in shear and in tension are shown in Fig. 12.

For specimens made from rolled I-beams, the ratio varied from 0.505 to 0.634. Tank steel plates had ratios between 0.509 and 0.534, while rolled soft steel plates ranged from 0.527 to 0.671. The ratio for different size specimens of the same material did not change very much, the average being 0.629.

Attention should be called to the fact that a number of the structural grade steels had a yield-point stress in shear, when determined by slotted plate specimens, considerably less than 60 per cent of the yield-point stress in tension. If the yield-point stress developed by hollow torsion specimens is considered to be correct, the above ratios would be still lower, as the values obtained on the slotted plate specimens are compatible with those obtained on the solid torsion specimens.

The addition of nickel and chromium increased the ratio between the yield-point stresses in shear and in tension to as much as 0.869.

The ultimate stress in shear when obtained on solid torsion bars was found to be greater than the tensile ultimate stress. This is due to the fact that the stress distribution at the ultimate load is not proportional to the strain. The slotted plate specimens however, gave ultimate shearing stresses about 85 per cent of the ultimate tensile stresses.

The results of these tests also indicated that the direction of rolling had no appreciable effect on the strength of the material. However, the material was found to be more ductile in the direction of rolling.

(b) Poisson's Ratio - If an elastic material is stretched by a tensile force, the longitudinal extension is accompanied by a lateral contraction. The ratio between the lateral and longitudinal strains is called Poisson's Ratio. In this investigation, all values of Poisson's ratio were determined from the measured lateral and longitudinal deformations of a specimen under tensile stress.

For isotropic materials there is a direct relation between the shearing and tensile modulus of elasticity and Poisson's ratio. This relation is as follows:

$$G = \frac{E}{2(1 + n)}$$

where G = shearing modulus of elasticity

E = tensile modulus of elasticity

n = Poisson's ratio (ratio of lateral to longitudinal strain)

The results presented in Table IV show that Poisson's ratio for the structural steels varied only between 0.271 and 0.302. The shearing modulus of elasticity as presented in Table IV shows a high degree of uniformity when calculated from the observed longitudinal and lateral strains while the shearing modulus obtained by direct measurements showed considerable variation.

A typical diagram showing the lateral, longitudinal and torsional strains of a structural steel is presented in Fig. 13. It is to be noted that the lateral strains indicated a sharp yield point at the same stress as did the longitudinal strains. However, on some specimens the lateral extensometers did not indicate the yielding of the material at exactly the same time as did the longitudinal extensometer. This indicates that the yielding of the material did not occur simultaneously over the entire length of the specimen, but started at one point and worked along the length of the specimen. As soon as the material began to yield at the point where the lateral extensometer was attached, the pointers on this extensometer moved very repidly. It should be understood that between the time that the longitudinal and lateral extensometers indicated a yielding of the material, there was no additional load put on the specimen.

Fig. 14 shows the lateral and longitudinal strains of two different specimens made of the same material. The similarity of these two independent tests serves as a good indication of the reliability of the method of measuring the lateral deformations.

(c) Fractures - In all cases the round specimens of structural steel had cup or semi-cup fractures. The flat specimens made from plates and I-beams also tended to form a cup-shaped fracture.

Fig. 15 shows the fractures of the tensile, torsion and slotted plate specimen of structural steel as rolled. The torsion fractures were quite smooth as were the slotted plate specimens. All of the structural steel tensile fractures showed a silky texture of the metal.

5. Physical Properties of Alloy Steels.

(a) Relative Strength - The tensile and shearing properties as well as Poisson's ratio for the ten alloy steels are presented in Table V. The tensile yield-point stress ranged from 37,500 to 53,000 lb. per sq.in. for steels in an annealed condition, and from 55,000 to 124,000 lb. per sq.in. for steels in a quenched condition. Since these alloy steels did not have a definite yield point, either in tension or in shear, a useful limit point was used to compare the strengths of the different materials. This limit, as has been stated, is the stress at which the rate of strain is twice as great as the rate of strain on the straight line portion of the diagram.

The annealed specimen which had the highest yield-point stress contained 0.43 per cent carbon and 3.47 per cent nickel. The quenched specimens having the highest yield-point stress contained 0.37 per cent of carbon, 1.18 per cent of chromium, and 0.16 per cent of vanadium. The yield-point stress was not obtained on the alloy steel which contained tungsten, and probably this material would have given the highest value.

The ultimate tensile stresses ranged from 67,400 to 96,150 lb. per sq.in. for the annealed and from 91,100 to 157,500 lb. per sq.in. for the quenched specimens. The quenched specimen having the greatest ultimate strength contained 0.34 per cent of carbon, 0.51 per cent chromium and 1.20 per cent of tungsten.

The shearing yield-point stresses, as determined on solid torsion specimens, ranged from 33,500 to 43,750 lb. per sq.in. for annealed and from 44,100 to 93,000 lb. per sq.in. for the quenched specimens.

In general, the ratios between the shearing and tensile yield-point stresses were greater for the annealed specimens than for the quenched specimens. The annealed specimens had ratios between 0.774 and 0.894, and the quenched from 0.662 to 0.809. The relation between the shearing and tensile yield points for these alloy steels is shown in Fig. 16. It should be noted that alloy steels both in annealed and quenched condition had a considerably greater ratio between the yield-point stresses than did the structural steels.

The ultimate stresses in shear for the quenched material were less than the ultimate stresses in tension, while the annealed specimens in general had greater ultimate stresses in shear than in tension. This indicates that the quenched specimens were not as ductile as the annealed, and that the change in stress distribution caused by excessive deformations was relatively small.

(b) Poisson's Ratio - Poisson's ratio for all the alloy steels was computed from the measured lateral and longitudinal strains and the values are presented in Table V. It was found that for the ten alloy steels this ratio ranged from 0.272 to 0.320. With the exception of the tungsten steel, there was little difference between Poisson's ratio for annealed and quenched specimens of the same material.

A typical diagram of the lateral, longitudinal and torsional strains of an alloy steel is shown in Fig. 17. Attention is called to the gradual transition from a straight line to a curve in all three cases. The proportional limit as found by the longitudinal deformations was also found by the lateral deformations. After the proportional linit was reached, the lateral strains increased at a faster rate than did the longitudinal strains so that Poisson's ratio approached the value of 0.50.

For the annealed and quenched alloy steels the observed modulus of elasticity in shear was generally greater than that calculated from the tensile modulus of elasticity and Poisson's ratio.

(c) Description of Fractures - Fig. 18 presents a few typical fractures of annealed and quenched alloy steels. The annealed specimens were in some cases a perfect cup fracture, while the corresponding quenched specimens showed a distinct star-shaped fracture. Other annealed specimens had star-shaped fractures and the corresponding quenched specimens had star-fractures with laminations. These laminations were usually on two diameters at right angles to each other.

(d) Ductility and Hardness of Alloy Steels - The Brinell hardness number, the percentage elongation and reduction of area of the alloy steels are presented in Table VI. The hardness numbers ranged from 146 to 285, and in all cases the quenched specimens were harder than their companion annealed specimens.

The elongation in two inches was measured for these alloy specimens and as they were all the same diameter the relative ductility of these steels is indicated directly from the per cent elongation. The annealed specimens were in all but one case, more ductile than the quenched specimens when the ductility was determined by the percentage elongation.

Although the relative strengths of these alloy steels cannot be compared exactly with their corresponding ductility, there is a relation between these two properties. Fig. 19 shows the relation between the tensile yield-point stress and percentage of elongation for the quenched specimens. In general, the greater the yield-point stress, the lower is the percentage of elongation.

VI. RESULTS OF EARLIER EXPERIMENTS

1. Relation Between Yield-Point Stress in Shear and Tension - The results of investigations on the relation between the yield-point stress in shear and in tension are presented in Table VII. The results obtained by Platt and Hayward show a ratio very close to 0.6. The yield point used to compute this ratio was determined by a drop of the beam of the testing machine. The yield point in shear was determined on solid torsion specimens.

Both Hancock and Turner used the proportional limit as a means of comparing the yield-point stresses in shear and in tension. Turner used both solid and hollow torsion specimens and all specimens were annealed. The results ranged from 0.503 to 0.577. Hancock's experiments show considerable variation and Scobes' tests, which are included in the group, show a ratio as low as 0.451. There is some doubt however, as to the accuracy with which these experiments were performed.

Seely and Putnam recommend the value of 0.6 of the tensile yield point as the criterion for the shearing yield point. They found that the ratio varied between 0.55 and 0.65 when measured by the proportional limit or useful limit.

2. Poisson's Ratio - Table VIII gives a resumé of the results of the more important investigations on Poisson's ratio. It is to be noted that both Stromeyer and Morrow conclude that the values of Poisson's ratio were not a constant for different materials. Stromeyer also concluded that the value of Poisson's ratio as determined by direct measurements, differs from that computed from the modulus of elasticity in shear and in tension. Wertheim's value of 0.2686 seems rather far fetched, as it does not seem possible to measure the deformations closely enough to warrant such a figure. Jasper has made an extensive investigation on Poisson's ratio and his values as found by direct measurement agree very closely with those calculated from the elasticity of the steel. However, his value of Poisson's ratio seems rather low in comparison to all other investigations.

VII. SUMMARY AND CONCLUSIONS

1. The apparatus developed for measuring lateral and torsional deformations proved to be very consistent and accurate.

2. The slotted plate specimens and solid torsion specimens gave approximately the same yield-point stress in shear. The ultimate shearing stress developed on a slotted plate specimen was about 85 per cent of the ultimate tensile stress and probably is as close to the correct value as is possible to obtain. The ultimate stress developed on a solid torsion specimen was generally equal to or greater than the ultimate tensile stress.

3. The average yield-point stress in shear of a hollow bar was about 80 per cent of that of a solid bar for three different grades of steel. The ratio, however, is different for each grade of steel.

4. The size of the test specimen had no effect on the elastic properties of the steel. However, there was a difference in the strength of these specimens due to the effect of the rolling of the original material from which the specimens were made. Specimens which included the material near the surface of the rolled section produced the greatest strength.

5. The structural steel showed a wide variation in the ratio between the yield-point stresses in shear and in tension. In general, the ratio was below 0.6 for specimens made from rolled plates and structural sections. The addition of an alloy such as nickel or chromium, raised this ratio considerably. The value of 0.6, which is generally used as a criterion for the ratio between the yield-point stress in shear and tension, does not always hold true and the use of this value should not be allowed until specific tests have been made on the steel under question.

6. Poisson's ratio for structural steel varied from 0.271 to 0.302. For all design purposes, the value of 0.30 seems to be justified.

7. For alloy steels, the ratio between the yield-point stresses in shear and in tension varied between 0.774 and 0.894 for annealed specimens, and between 0.662 and 0.809 for quenched specimens.

8. Poisson's ratio for alloy steels varied between 0.272 and 0.320. After the elastic limit of the alloy steels was reached, Poisson's ratio increased and tended to reach a value of 0.50.

9. The strength of the structural steels was not found to be affected by the direction of rolling, but the ductility was less in the perpendicular direction than it was parallel to the direction of rolling.

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* POISSON'S RATIO - Proceedings, Physical Society, Vol. XVIII, p. 582.

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12. Commission des Methodes d'Essai des Materiaux de Construction, Vol. 3, p. 6, (1895).

13. Johnson's MATERIALS OF CONSTRUCTION - 1930, p.10.

IX. TABLES AND FIGURES

T A B L E S

TABLE I - CHEMICAL COMPOSITION OF ALLOY STEELS

Steel No.	Chemical Analysis - per cent										Treatment
	C.	Mn.	P.	S.	Si.	Ni.	Cr.	V.	Mo.	W.	
1 a 1 q	0.27 0.27	0.72 0.72	0.014 0.014	0.024 0.024	0.21 0.21						1450° Furnace Cooled 1600° Water, 1100° Drawn
2 a 2 q	0.38 0.38	0.65 0.65	0.015 0.015	0.029 0.029	0.22 0.22						1450° Furnace Cooled 1600° Water, 1100° Drawn
3 a 3 q	0.43 0.43	0.64 0.64	0.015 0.015	0.023 0.023	0.20 0.20	3.47 3.47					1450° Furnace Cooled 1450° Oil, 1100° Drawn
4 a 4 q	0.40 0.40	0.51 0.51	0.019 0.019	0.028 0.028	0.20 0.20	1.65 1.65	0.99 0.99				1450° Furnace Cooled 1530° Oil, 1100° Drawn
5 a 5 q	0.32 0.32	0.60 0.60	0.014 0.014	0.019 0.019	0.16 0.16	1.92 1.92	0.86 0.86		0.30 0.30		1450° Furnace Cooled 1530° Oil, 1100° Drawn
6 a 6 q	0.31 0.31	1.66 1.66	0.015 0.015	0.024 0.024	0.25 0.25						1450° Furnace Cooled 1525° Oil, 1100° Drawn
7 a 7 q	0.34 0.34	0.92 0.92	0.032 0.032	0.033 0.033	0.20 0.20		0.51 0.51			1.20 1.20	1450° Furnace Cooled 1600° Oil, 1100° Drawn
8 a 8 q	0.37 0.37	0.71 0.71	0.024 0.024	0.037 0.037	0.33 0.33		1.18 1.18	0.16 0.16			1450° Furnace Cooled 1600° Oil, 1100° Drawn
9 a 9 q	0.33 0.33	0.54 0.54	0.025 0.025	0.029 0.029	0.21 0.21		0.78 0.78		0.24 0.24		1450° Furnace Cooled 1600° Oil, 1100° Drawn
10	0.20	1.19	0.033	0.019	0.67		0.45				As rolled

a = annealed q = quenched

TABLE II - SOLID AND HOLLOW TORSION TESTS

Soft Steel - C. 0.18; Mn. 0.43; Ph. 0.01; S. 0.03; Si. 0.06; Ni. 0.03

Test	Yield-Point	Ultimate	$\frac{\text{Y.P.Hollow}}{\text{Y.P. Solid}}$	$\frac{\text{Ult.Solid Torsion}}{\text{Ult.Tensile}}$
Tensile	30,000	55,000		
Solid -Torsion	20,200	61,400	0.972	1.12
Hollow-Torsion	19,650	58,000		

Medium Steel - C. 0.16; Mn. 0.45; Ph. 0.014; S. 0.024; Si. 0.15; Ni. 0.23; Cr. 0.02

Test	Yield-Point	Ultimate	$\frac{\text{Y.P. Hollow}}{\text{Y.P.Solid}}$	$\frac{\text{Ult.Solid Torsion}}{\text{Ult.Tensile}}$
Tensile	30,800	57,650		
Solid -Torsion	22,750	68,000	0.906	1.18
Hollow-Torsion	20,600	53,500		

Hard Steel - C. 0.18; Mn. 0.90; Ph. 0.028; S. 0.087; Si. 0.24; Ni. 0.10; Cr. 0.08

Test	Yield-Point	Ultimate	$\frac{\text{Y.P.Hollow}}{\text{Y.P. Solid}}$	$\frac{\text{Ult.Solid Torsion}}{\text{Ult.Tensile}}$
Tensile	41,800	69,900		
Solid-Torsion	34,050	79,800	0.820	1.14
Hollow-Torsion	27,950	62,200		
		Average	--- 0.90	

TABLE III - TENSILE AND SHEARING PROPERTIES OF STRUCTURAL GRADE STEEL

Type of Steel	Tension		Shear		Y.P.Shear / Y.P.Tension
	Yield-Point Stress	Ultimate Stress	Yield-Point Stress	Ultimate Stress	
	lb. per sq.in.		lb. per sq.in.		
Web of I-beam No. 1	37,340	58,810	23,650		0.634
Web of I-beam No. 2	37,970	59,260	22,500	50,750	0.593
Web of I-beam No. 3	40,800	59,370	22,300	50,200	0.546
Web of I-beam No. 4	39,550	57,800	24,500	50,600	0.620
Tank Steel Plate WB-1	43,250	62,000	22,000	53,500	0.509
Tank Steel Plate WB-2	47,810	60,900	24,500	51,300	0.513
Tank Steel Plate WB-3	49,600	61,425	26,470	51,600	0.534
Web of I-beam WB-4	43,500	61,600	22,000	53,400	0.505
Web of I-beam WB-5	51,300	66,650	29,200	55,630	0.570
Web of I-beam CT (1-4)	47,000	63,900	25,000	53,300	0.531
Web of I-beam CT (5-6)	44,660	62,100	25,800	53,100	0.577
Plate WB- 6	33,080	46,800	17,450	46,900	0.527
Plate WB- 7	33,700	48,400	18,600	45,850	0.551
Plate WB- 8	29,680	46,080	19,920	46,250	0.671
Plate WB- 9	30,280	46,980	18,480	44,800	0.610
Plate WB-10	30,270	47,150	18,400	46,250	0.607
Plate S-1	30,650	60,200	19,590	54,400	0.638
Plate S-2	26,900	60,400	16,500	49,200	0.613
0.5-in. rod	35,350	60,150	22,500*	68,800*	0.637
1.0-in. rod	36,400	61,250	22,650*	66,250*	0.623
1.5-in. rod	39,350	62,500	24,700*		0.628
Soft Steel Rod	30,000	55,000	20,200*	61,400*	0.674
Medium Steel [a]	30,800	57,650	22,750*	68,000*	0.739
Hard Steel Rod[a]	41,800	69,900	35,500*	79,800*	0.850
Nickel Steel [a]	48,000	91,400	41,700*	91,400*	0.869

* Solid torsion specimen, all others plate specimens.

a Annealed.

TABLE IV - TENSILE AND SHEARING MODULUS OF ELASTICITY

AND POISSON'S RATIO OF STRUCTURAL GRADE STEEL

Description	Tensile Modulus of Elasticity	Poisson's Ratio Observed	Shearing Modulus of Elasticity	
			Observed	Calculated
	lb./sq.in.		lb. per sq. in.	
0.5-in. dia.rod	29,000,000	0.302	12,600,000	11,100,000
1.0-in. dia.rod	29,500,000	0.299	11,800,000	11,350,000
1.5-in. dia.rod	29,600,000	0.302	12,400,000	11,350,000
Web of I-beam S-1	29,200,000	0.292	11,330,000	11,300,000
Web of I-beam S-2	29,050,000	0.278	11,900,000	11,400,000
0.5-in. dia.rod	29,400,000	0.271	*	11,560,000
1.5-in. dia.rod	29,800,000	0.278	*	11,680,000
* Not observed				

TABLE V - TENSILE AND SHEARING PROPERTIES OF ALLOY STEELS

Steel No.	Tension			Poisson's Ratio	Shear				Y.P.Shear / Y.P.Tension Ratio
	Modulus of Elasticity	Yield-Point Stress	Ultimate Stress		Modulus of Elasticity		Yield-Point Stress	Ultimate Stress	
	millionths lb./sq.in.	lb. per sq. in.		Observed	Observed	Calculated*	lb. per sq.in.		
					mill. lb. per sq. in.				
1 a 1 q	27.50 29.60	37,500 55,000	67,400 91,100	0.316 0.310	11.78 11.975	10.46 11.30	33,500 44,100	75,900 90,600	0.894 0.803
2 a 2 q	28.75 30.00	41,500 57,750	75,700 99,500	0.287 0.296	11.67 12.38	11.18 11.58	36,200 46,650	79,800 96,700	0.872 0.809
3 a 3 q	30.00 28,20	53,000 82,200	94,400 117,000	0.308 0.298	12.11 11.66	11.50 10.88	41,500 64,750	90,600 106,800	0.784 0.787
4 a 4 q	28.80 29.05	43,750 91,000	89,900 129,150	0.299 0.290	11.32 12.085	11.10 11.28	33,800 66,500	90,600 115,000	0.774 0.730
5 a 5 q	28.70 28.50	49,600 105,000	96,150 140,000	0.288 0.285	11.50 11.70	11.15 11.10	40,000 69,500	95,750 122,350	0.805 0.662
6 a 6 q	27,85 28.65	43,250 78,500	84,900 112,000	0.295 0.296	12.00 12.095	10.77 11.08	36,000 58,000	84,300 100,650	0.831 0.740
7 a 7 q	28.50 29.40	48,000 **	82,500 157,500	0.320 0.281	12.70 12.165	10.80 11.47	42,000 90,000	84,850 134,950	0.875 ---
8 a 8 q	29.35 30,00	49,250 124,000	88,700 151,350	0.289 0.279	11.75 12.50	11.40 11.75	43,750 93,000	89,500 131,650	0.889 0.750
9 a 9 q	28.55 28.75	42,500 90,500	76,700 126,500	0.288 0.272	12.00 11.845	11.10 11.30	35,000 63,750	87,350 114,000	0.824 0.705
10	30.425	54,300	85,600	0.276	11.875	11.92	31,100	84,200	0.573
* **	Calculated from observed modulus of elasticity and Poisson's Ratio. Yield-Point Stress not observed.								

TABLE VI - HARDNESS AND DUCTILITY OF ALLOY STEELS

Steel No.	Brinell Hardness No.	Per Cent Elongation in 2 in.	Per Cent Reduction of Area	Appearance of Tensile Fracture
1 a	153	46.5	64.0	Cup
1 q	191	42.0	70.5	Star
2 a	146	44.5	55.6	Cup Medium Grained
2 q	204	40.0	65.3	Star Finely Grained
3 a	187	33.0	44.7	Cup Finely Grained
3 q	226	33.5	58.2	Star Very Fine Grain
4 a	170	39.5	54.5	Irregular Cup Finely Grained
4 q	224	34.0	59.2	Ruptured Badly Laminated
5 a	202	37.3	57.6	Semi-cup Finely Grained
5 q	229	32.0	63.7	Irregular Star Badly Laminated
6 a	169	42.0	54.5	Cup Finely Grained
6 q	204	33.0	57.0	Step - Laminated
7 a	185	40.0	56.0	Cup Finely Grained
7 q	285	27.0	52.9	Star - Laminated
8 a	179	41.5	62.1	Star Finely Grained
8 q	285	24.5	48.5	Star - Slightly Laminated
9 a	170	48.0	66.0	Cup Finely Grained
9 q	229	28.0	59.5	Star Finely Grained
10	156	30.3		Square, Laminated

TABLE VII - RESULTS OF EARLIER EXPERIMENTS ON THE YIELD POINT OF STEEL

Platt and Hayward (1)

Material	Torsion Yield Point / Tensile Yield Point
Wrought Iron	0.598
Siemens Martin Steel	0.604
Bessemen Steel	0.647
Crucible Steel	0.623
Rivet Steel	0.571
Cast Steel	0.604

L. B. Turner (2)

Material	Torsion Propor.Limit / Tensile Propor.Limit
Mild Steel - 0.15% Carbon	0.519
Mild Steel - 0.32% Carbon	0.577
Tool Steel - 1.25% Carbon	0.568
Nickle Steel - 3.01% Nickle	0.503

Seely and Putnam (3)

Material	Torsion Propor.Limit / Tensile Propor.Limit
Soft Steel-small spec.	0.558
Soft Steel-large spec.	0.680
Mild Steel	0.600
Medium Steel	0.597
Vanadium Steel	0.526
Nickle Steel	0.594
Chrome-Nickle Steel	0.642

E. L. Hancock (4)

Material	Torsion Propor.Limit / Tensile Propor.Limit
Steel	0.500
Nickle Steel	0.497
Mild Carbon Steel	0.649
Steel (Scoble)	0.451
Carbon Steel	0.688
Rivet Steel	0.602
Nickle Steel	0.643

1. Proceedings, Institute of Civil Engineers, Vol.90, 1888
2. Engineering (London), February, 1909 and July, 1911
3. Bulletin No.115, University of Illinois, 1919
4. Proceedings, A.S.T.M., 1908

TABLE VIII - RESULTS OF EARLIER EXPERIMENTS ON POISSON'S RATIO

Investigator	Material	Poisson's Ratio
Bauschinger (1)	Mild Steel	0.29
Stromeyer (2)	Mild Steel	0.27 - 0.30
Morrow (3)	Mild Steel	0.27 - 0.28
Wertheim (4)	Steel	0.2686
Jasper (5)	Steel - 0.02% Carbon	0.197
Jasper	Steel - 0.41% Carbon	0.241
Jasper	Steel - 0.90% Carbon	0.241
Jasper	Steel - 1.20% Carbon	0.260
Jasper	Steel - 3.50% Nickle	0.265
Jasper	Steel - Chromium-Ni.	0.261

1 - Civilingenieur, XXV, 81

2 - Proceedings, Royal Society, LV, 373

3 - Proceedings, Physical Society, XVIII, 582

4 - Comm. des Methodes d'Essai des Materiaux de Construction, 1895, Vol. 3

5 - Proceedings, A. S. T. M., 1924

F I G U R E S

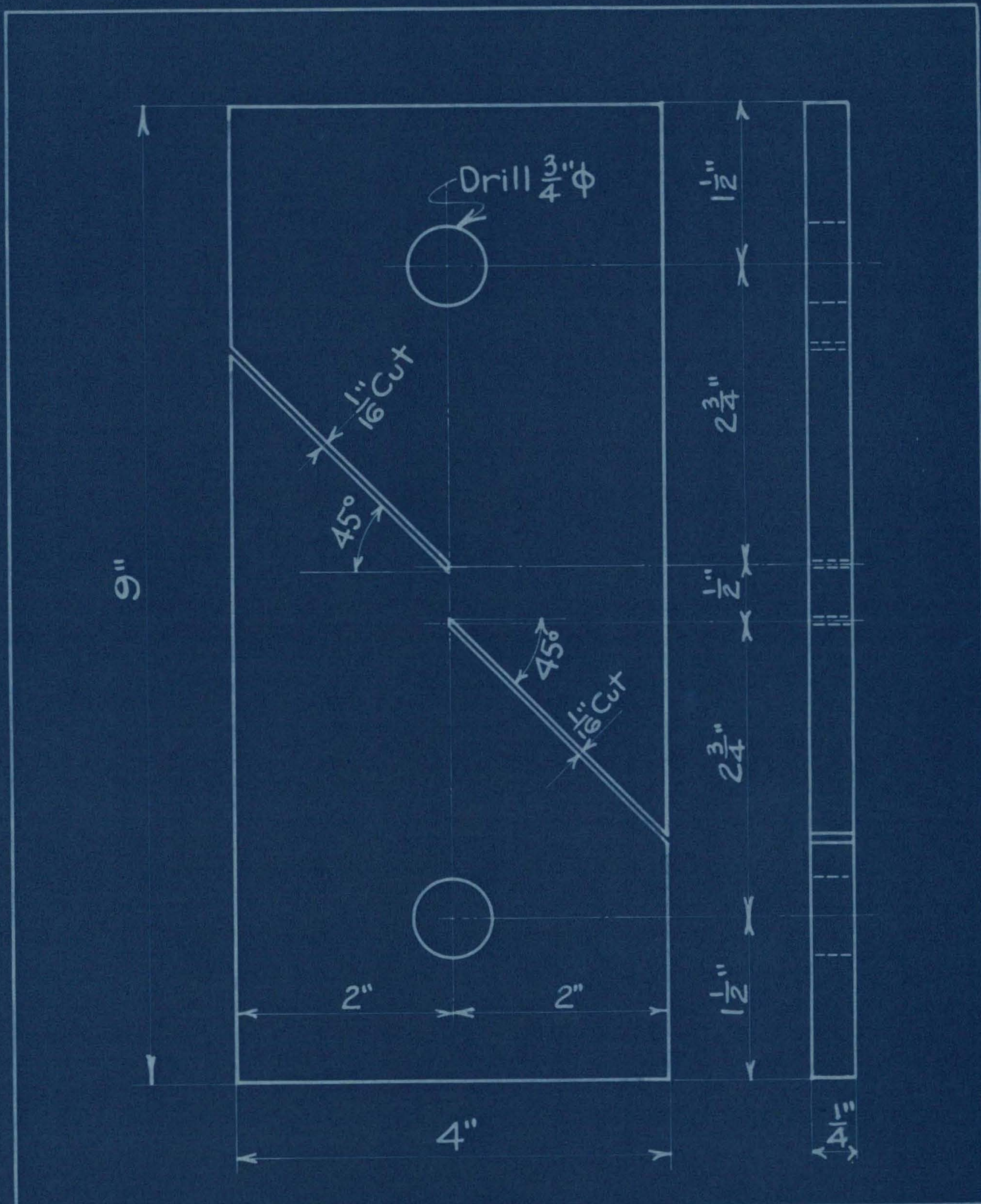

FIG. 1 – TYPICAL SLOTTED PLATE SPECIMEN

Fig. 2 - Photo-Elastic Picture of
Slotted Plate Specimen

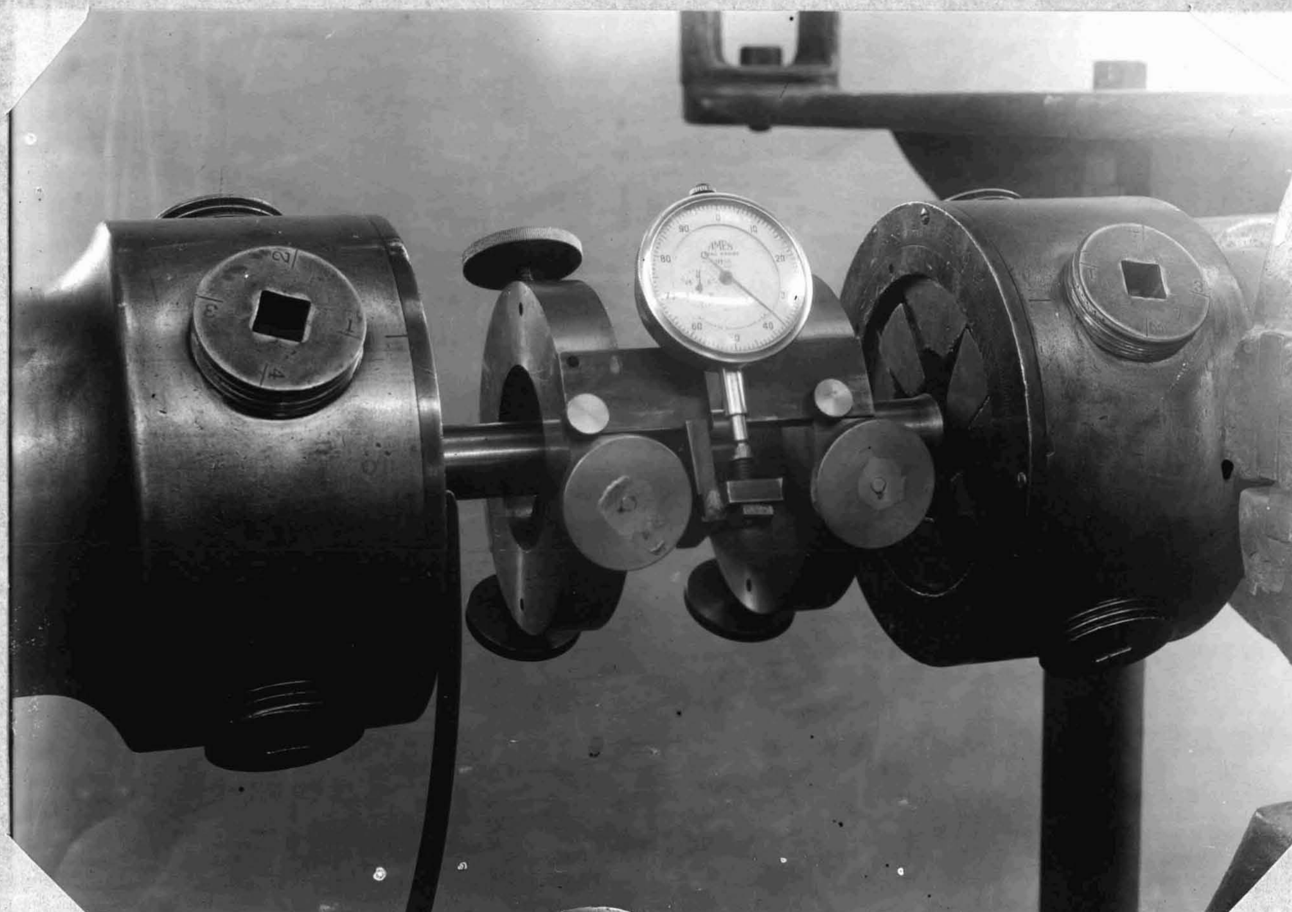

Fig. 3 - Apparatus for Measuring Torsional Deformations

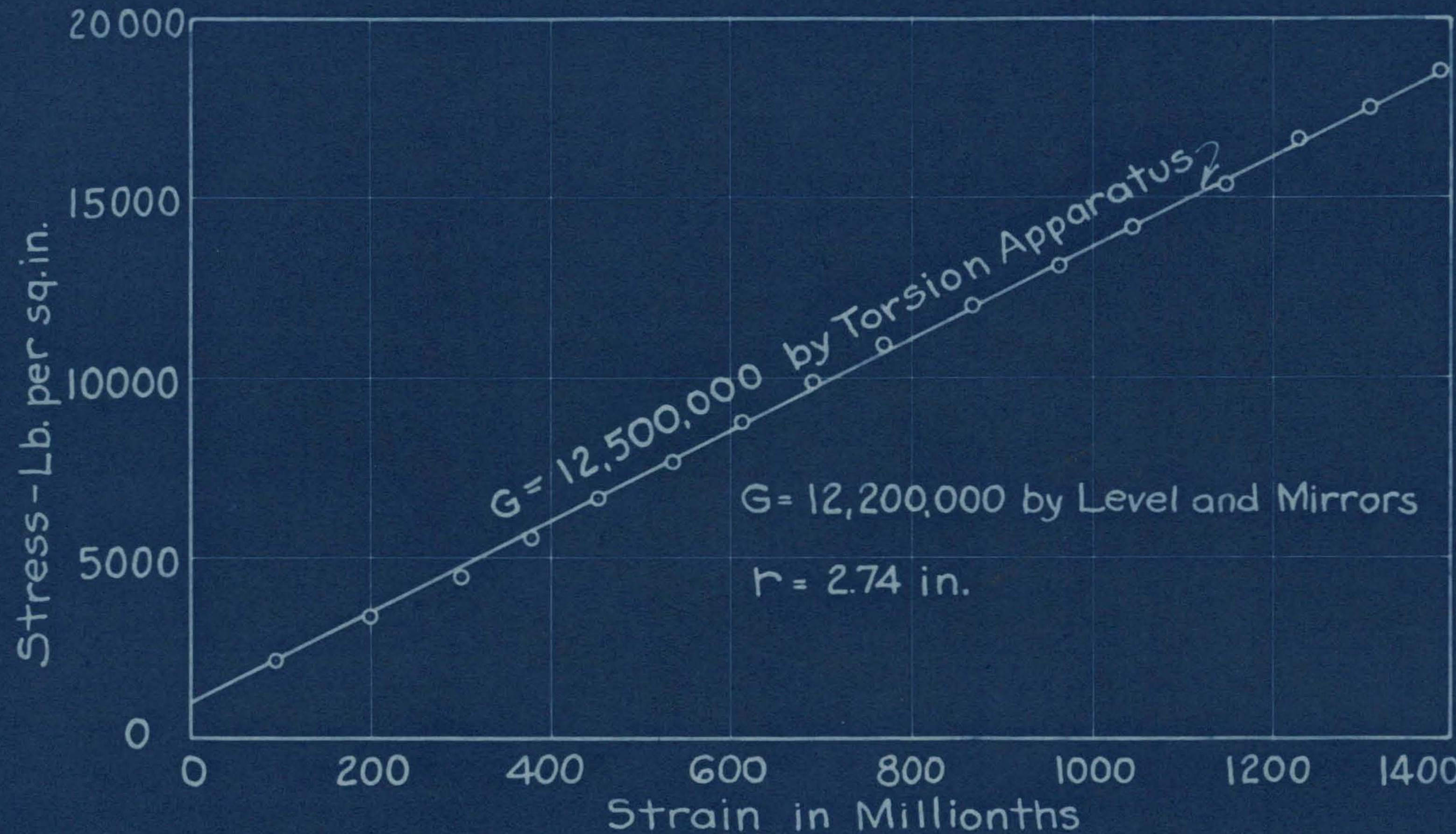

FIG. 4 CALIBRATION CURVE OF TORSION APPARATUS

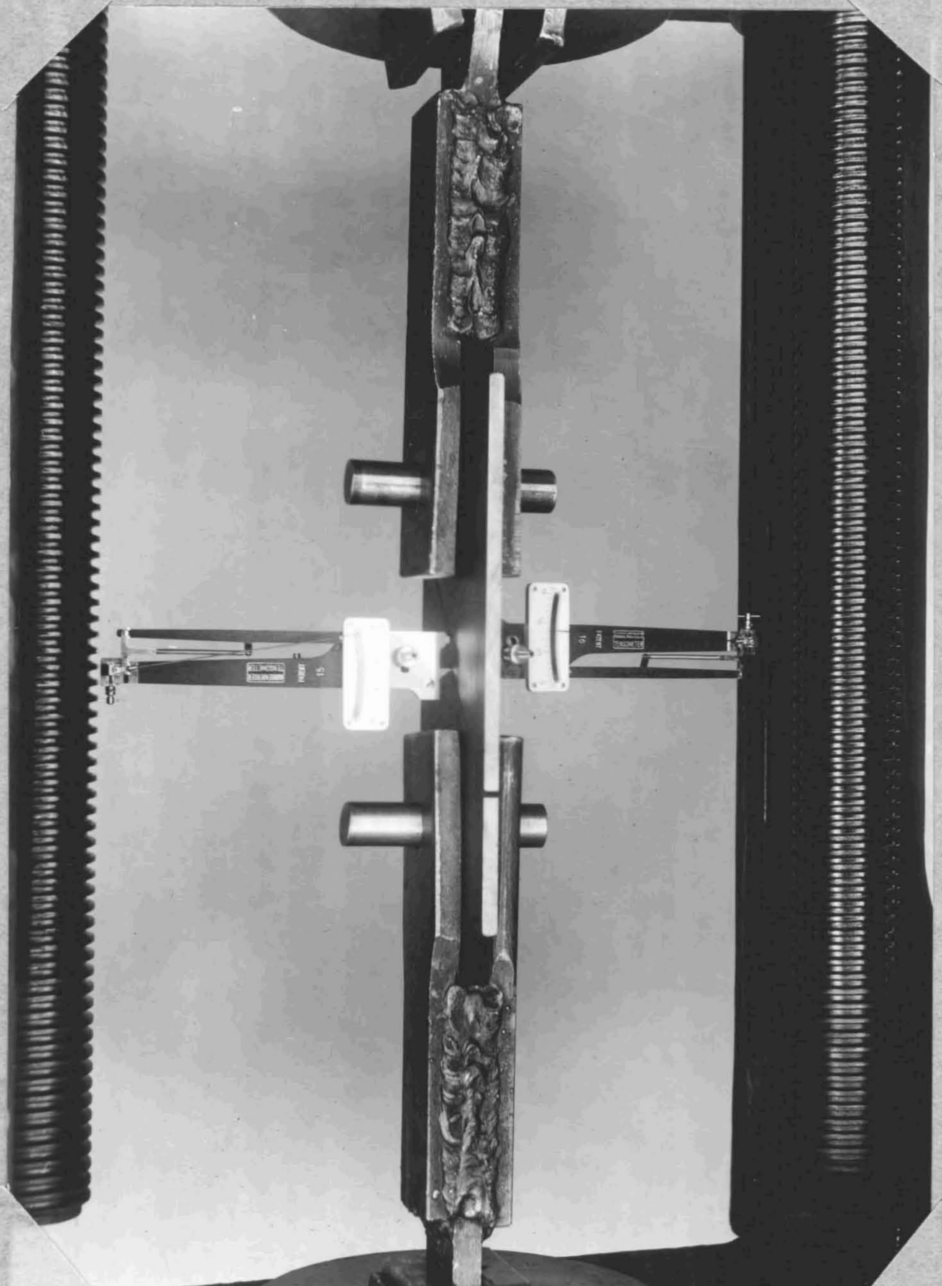

Fig. 5 - Slotted Plate Specimen With
Huggenberger Extensometers

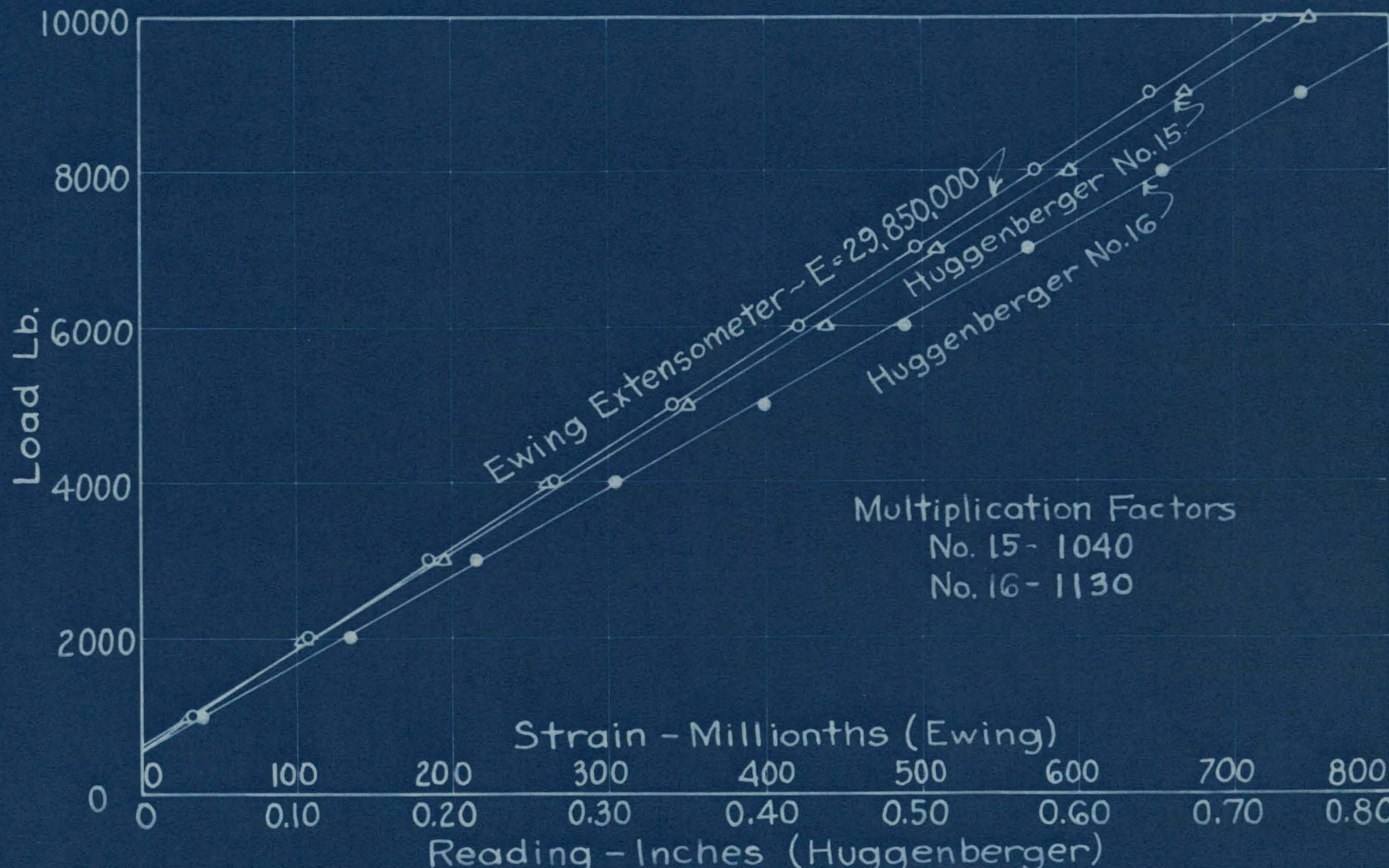

FIG 6 - CALIBRATION CURVES OF HUGGENBERGER EXTENSOMETERS No. 15 & 16

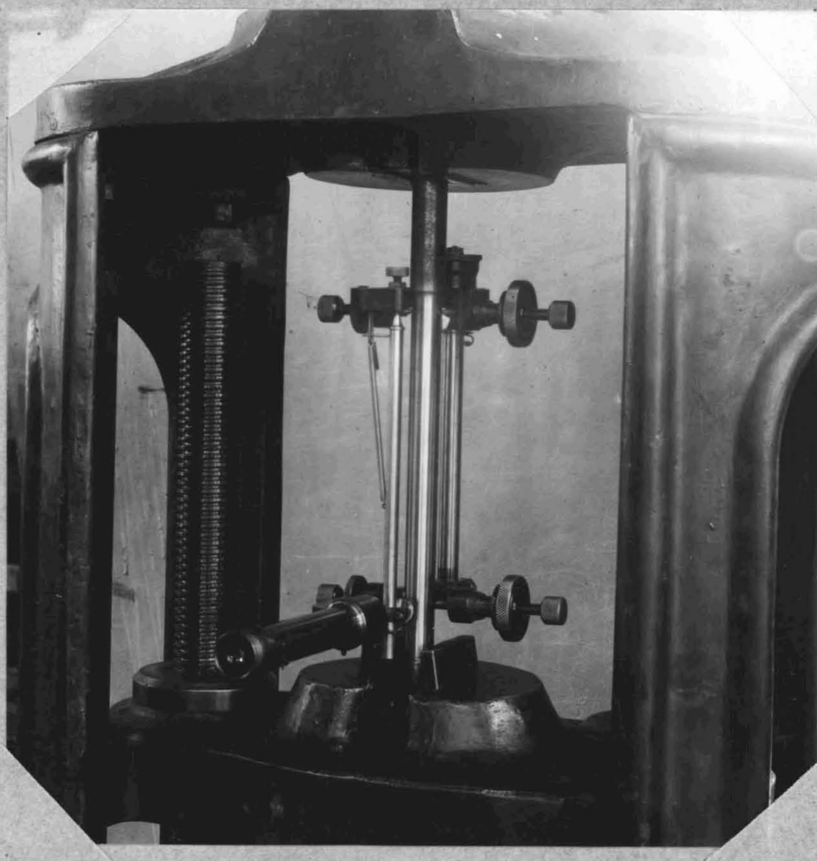

Fig. 7 - Ewing Extensometer

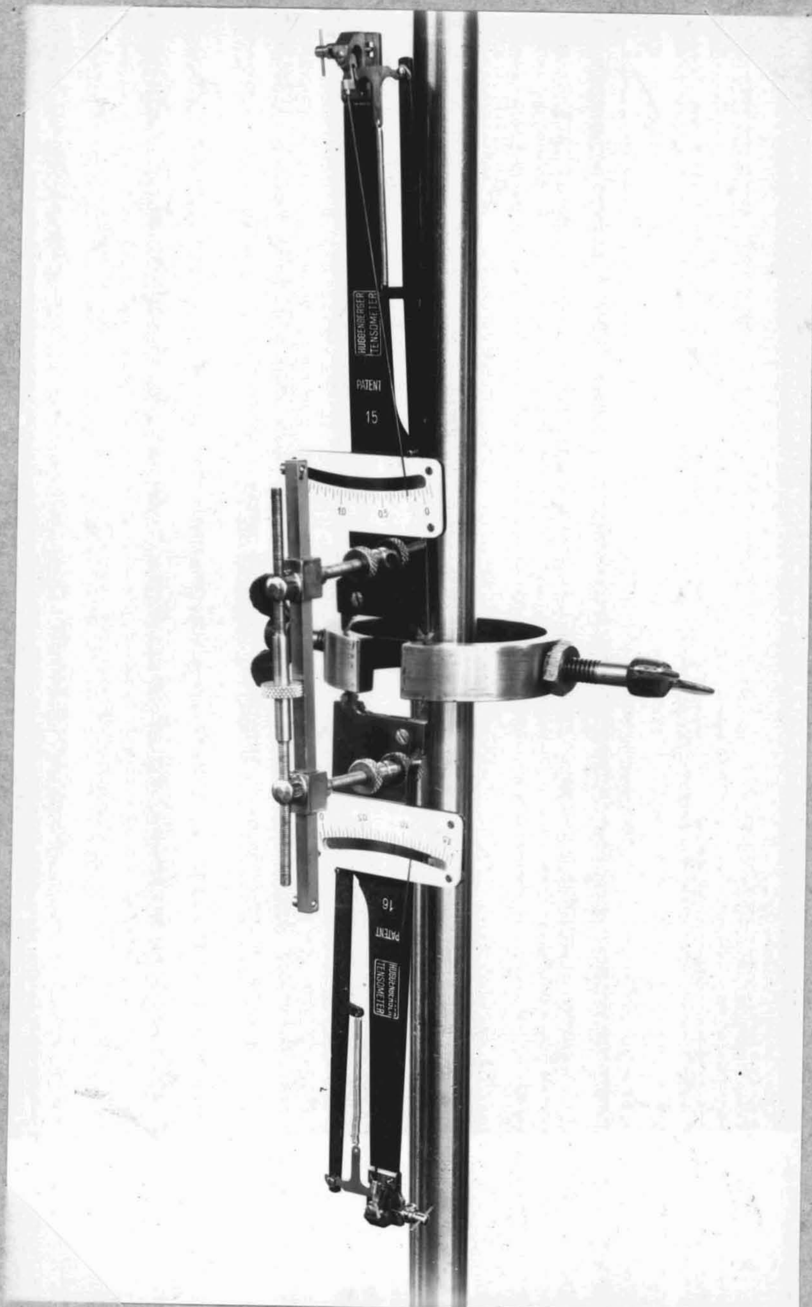

Fig. 8 - Apparatus for Measuring
Lateral Deformations

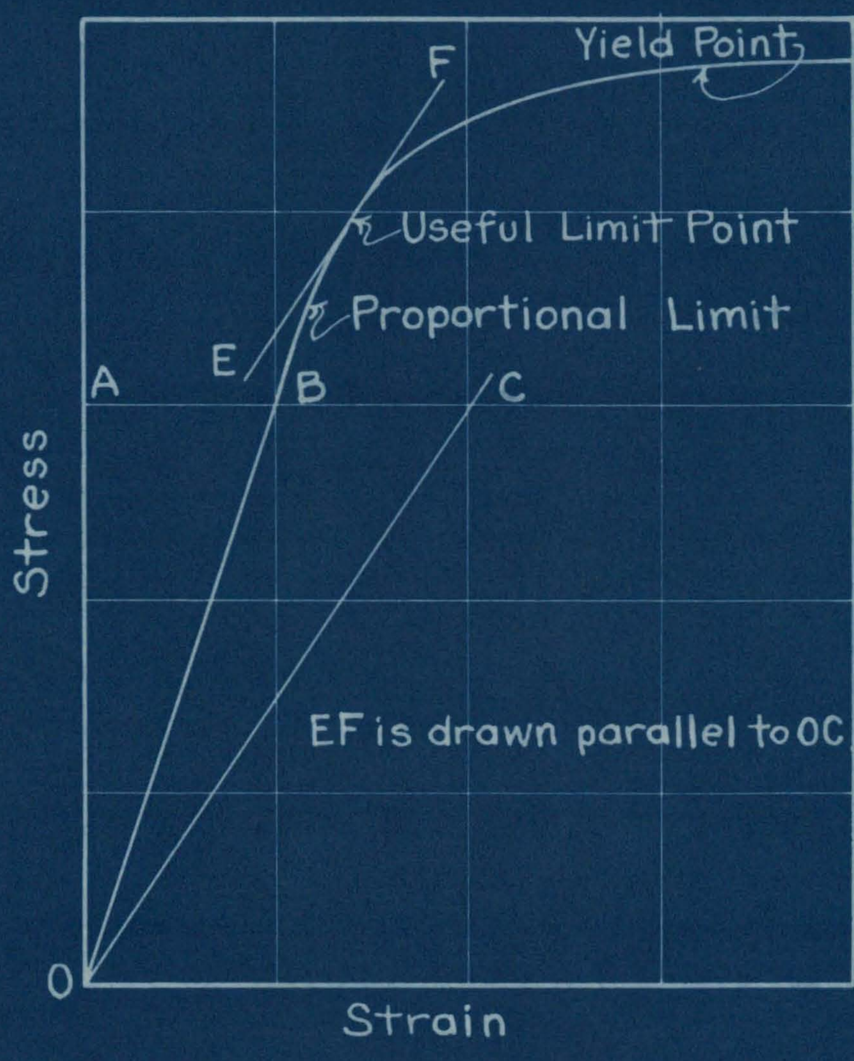

FIG 9 STRESS-STRAIN DIAGRAM
SHOWING USEFUL LIMIT POINT

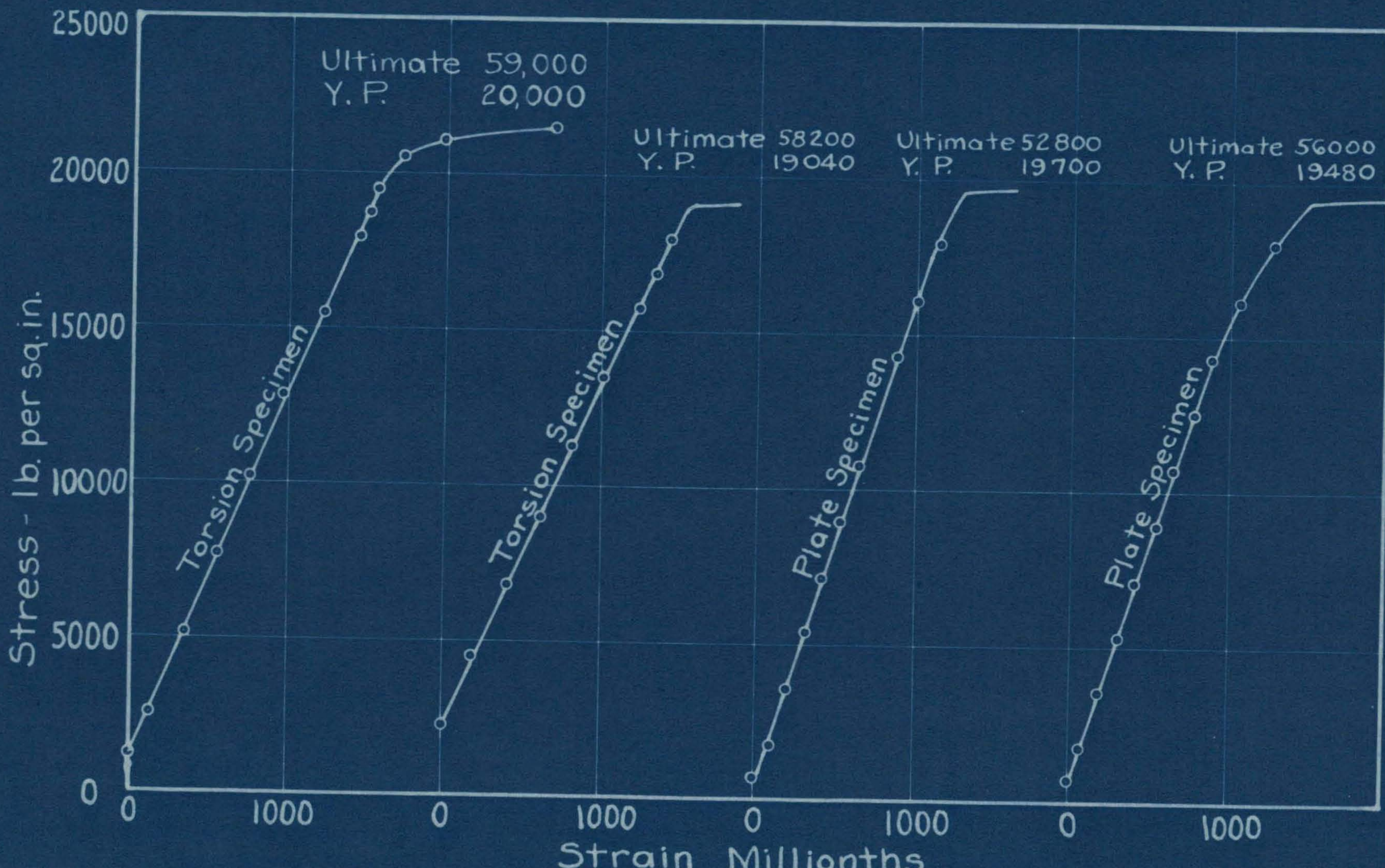

FIG 10 SHEAR TESTS OF SOLID TORSION AND SLOTTED PLATE SPECIMENS

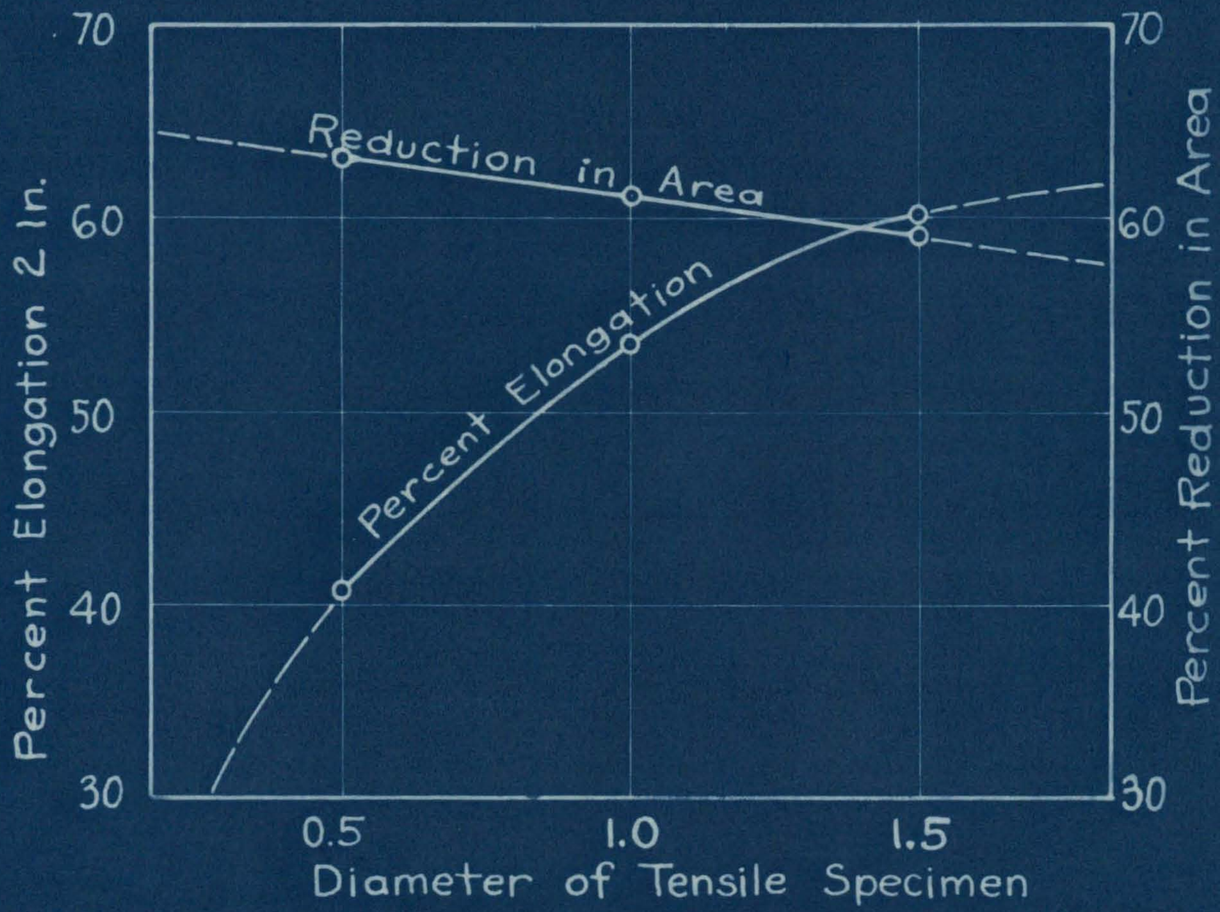

FIG 11 EFFECT OF THE SIZE OF SPECIMEN ON THE MEASURED DUCTILITY OF STRUCTURAL STEEL.

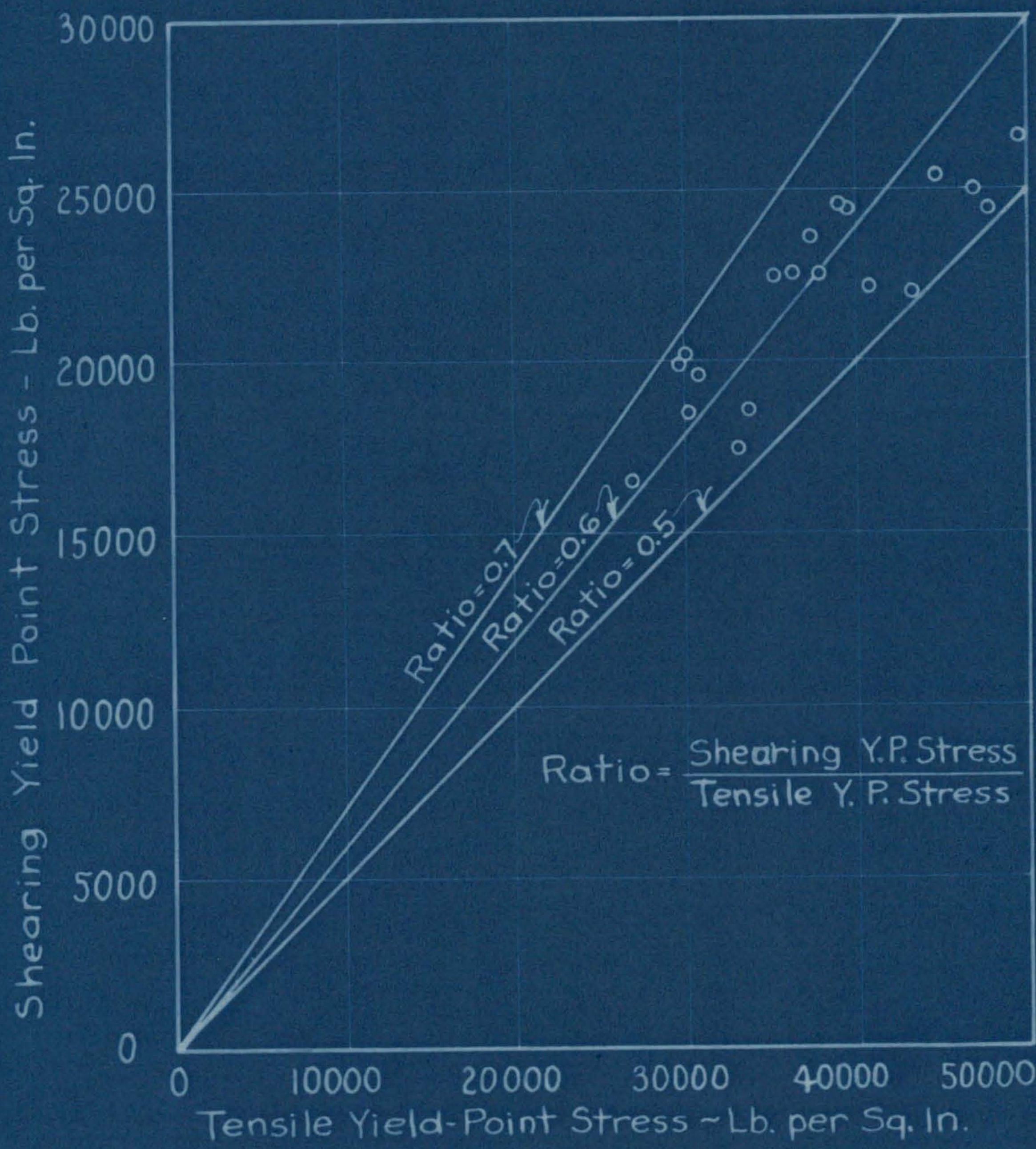

FIG 12 RELATION BETWEEN SHEARING AND TENSILE YIELD-POINT STRESSES OF STRUCTURAL STEEL

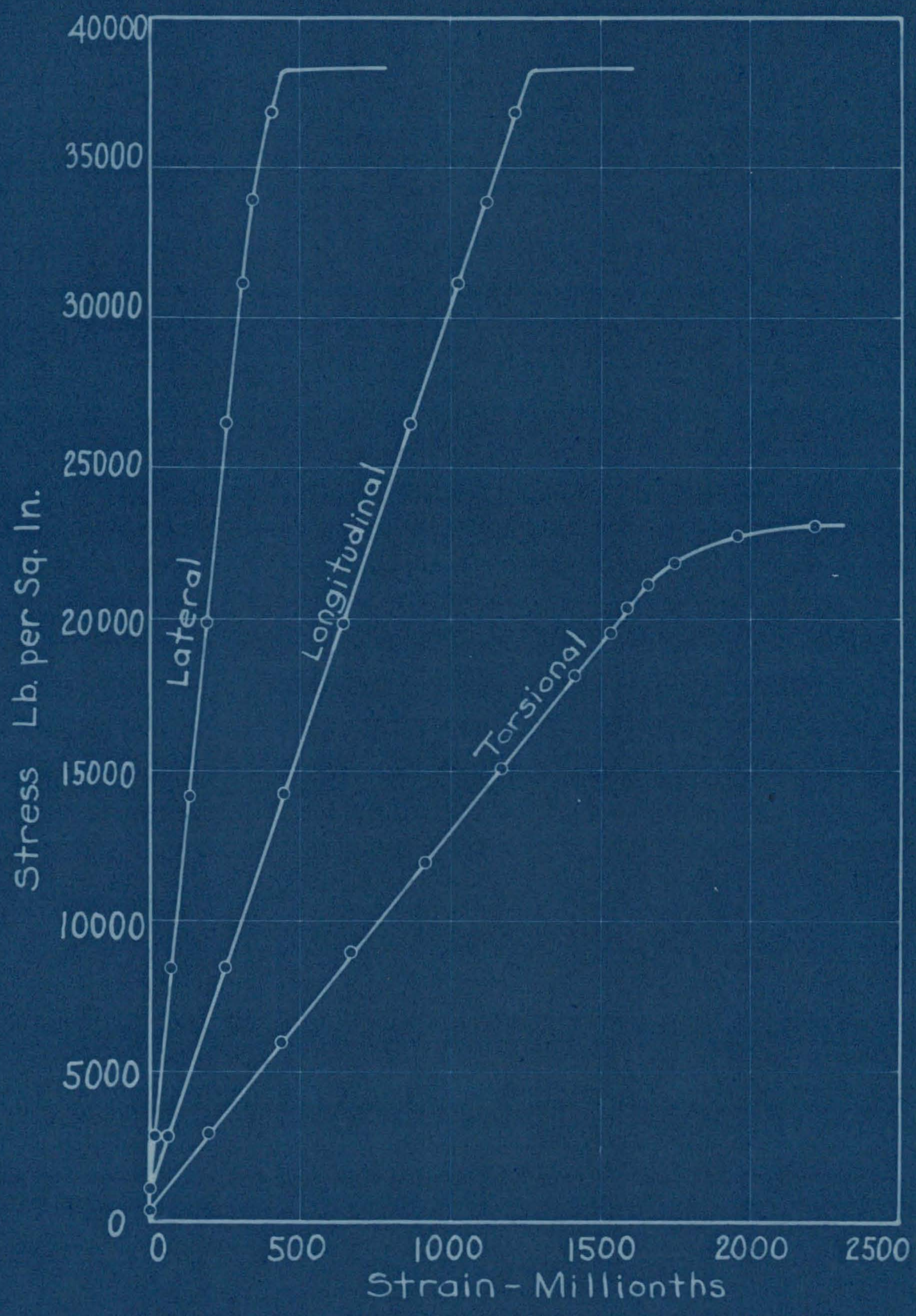

FIG 13 TYPICAL DEFORMATION DIAGRAM FOR STRUCTURAL STEEL

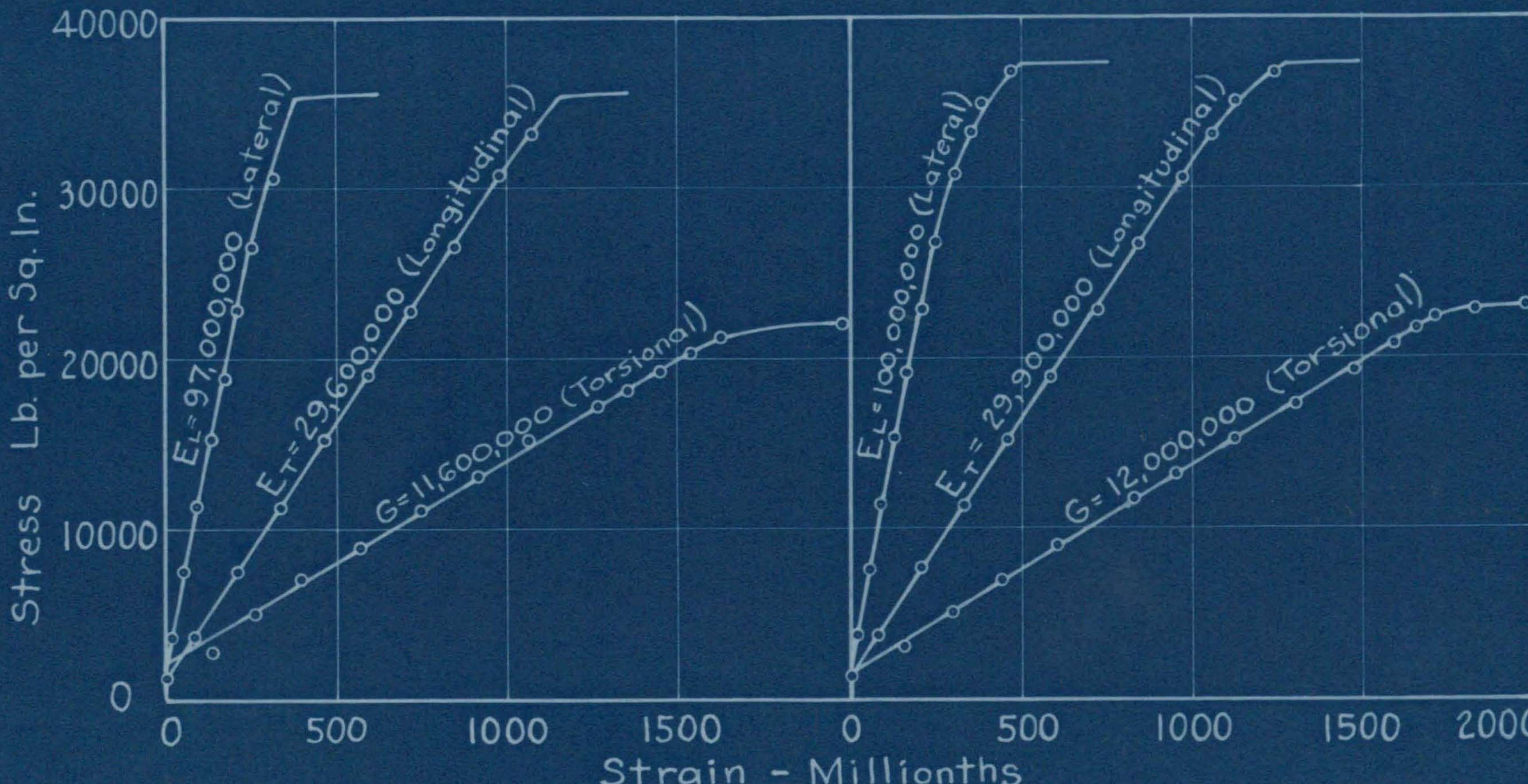

FIG 14 DEFORMATION CURVES FOR SPECIMENS OF THE SAME MATERIAL

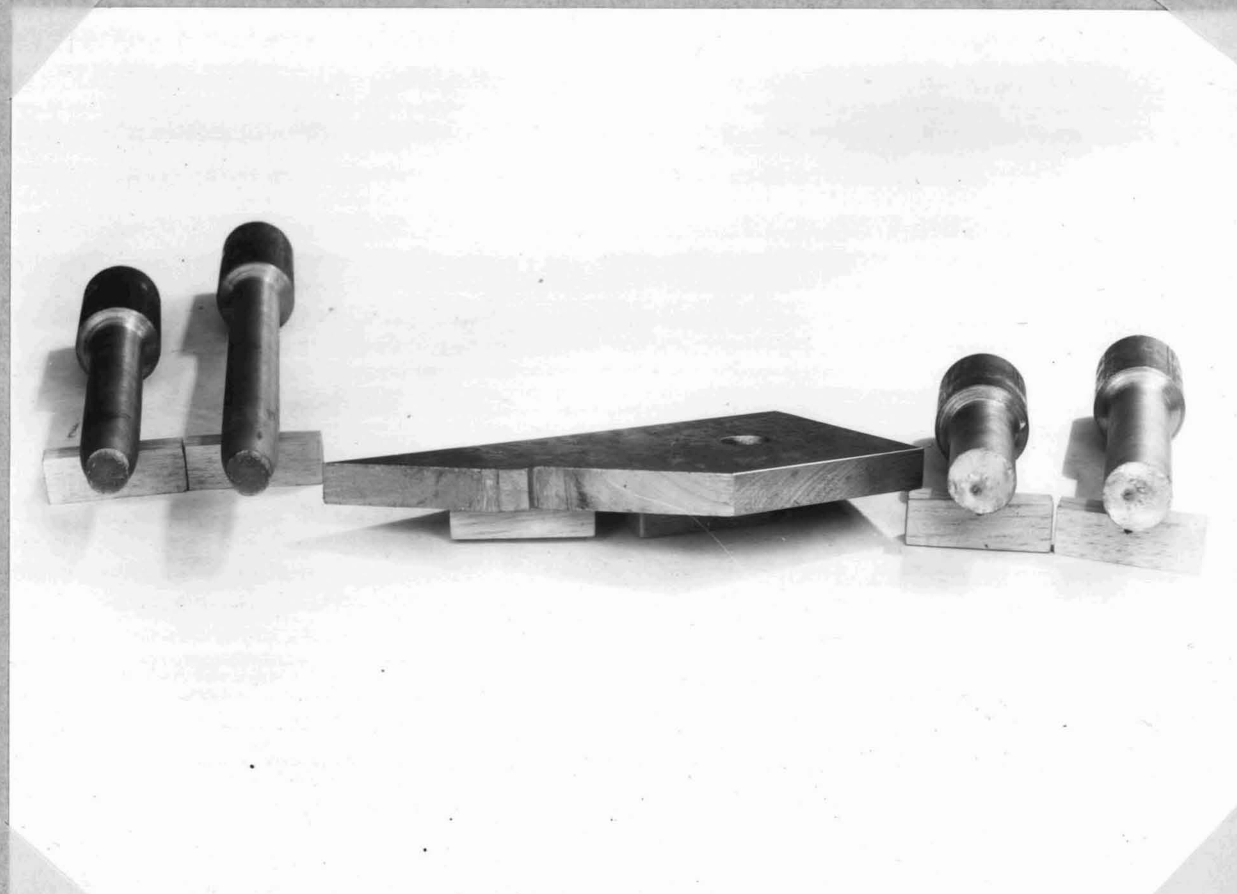

Fig. 15 - Fractures of Tensile, Torsion and Slotted Plate Specimens of Structural Steel

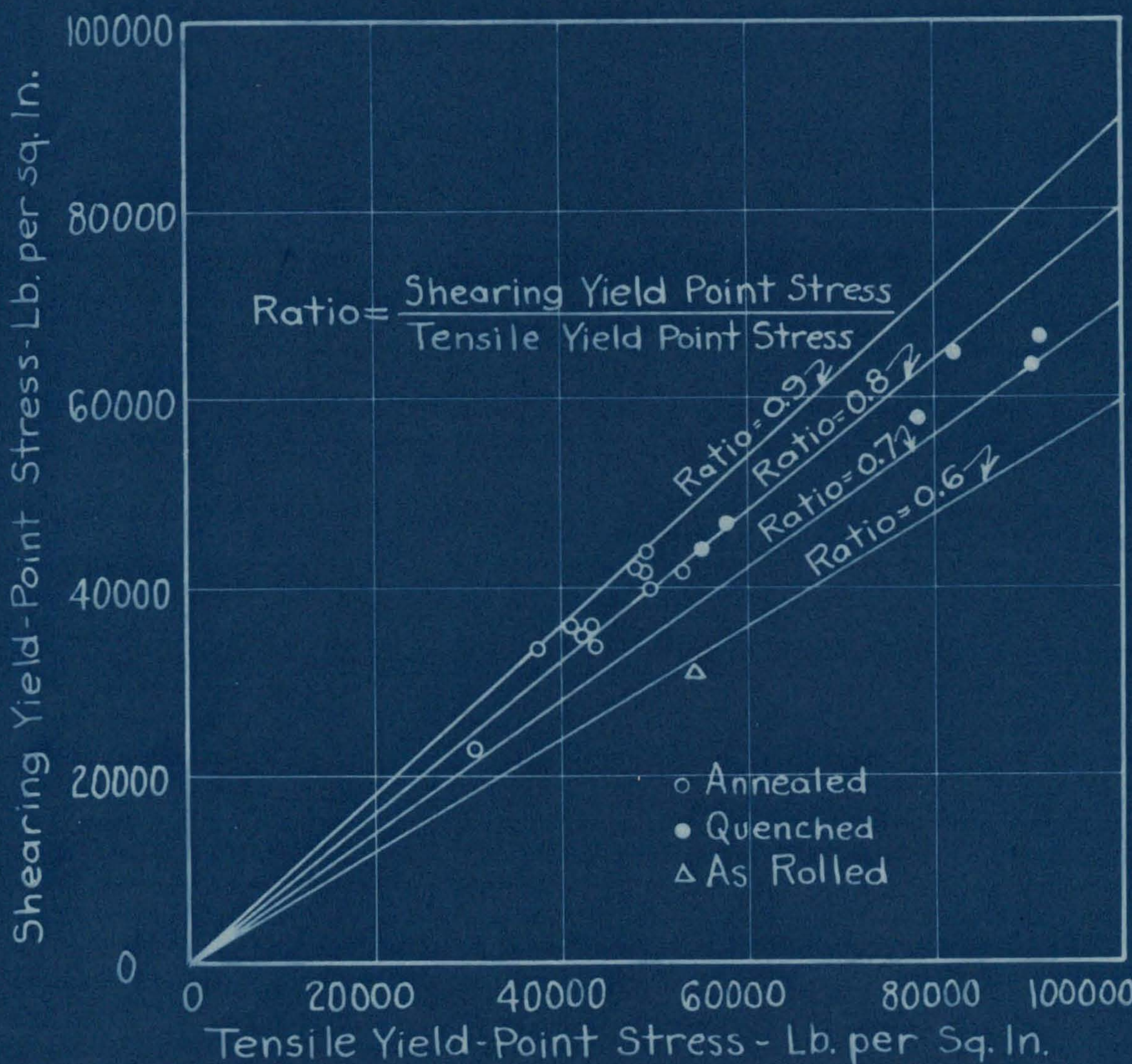

FIG 16 RELATION BETWEEN SHEARING AND TENSILE YIELD-POINT STRESSES OF ALLOY STEELS

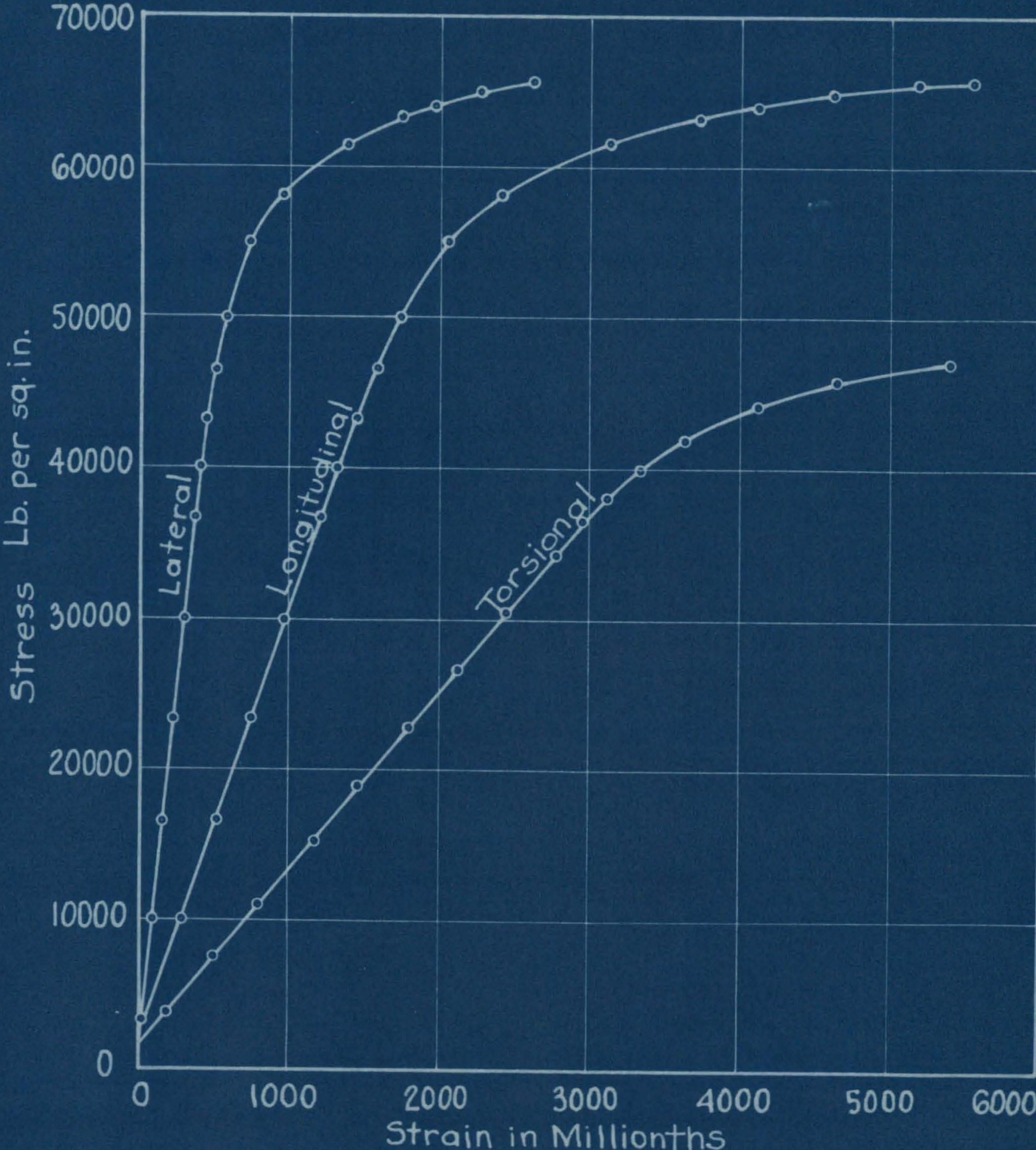

FIG 17 TYPICAL DEFORMATION DIAGRAM FOR ALLOY STEEL

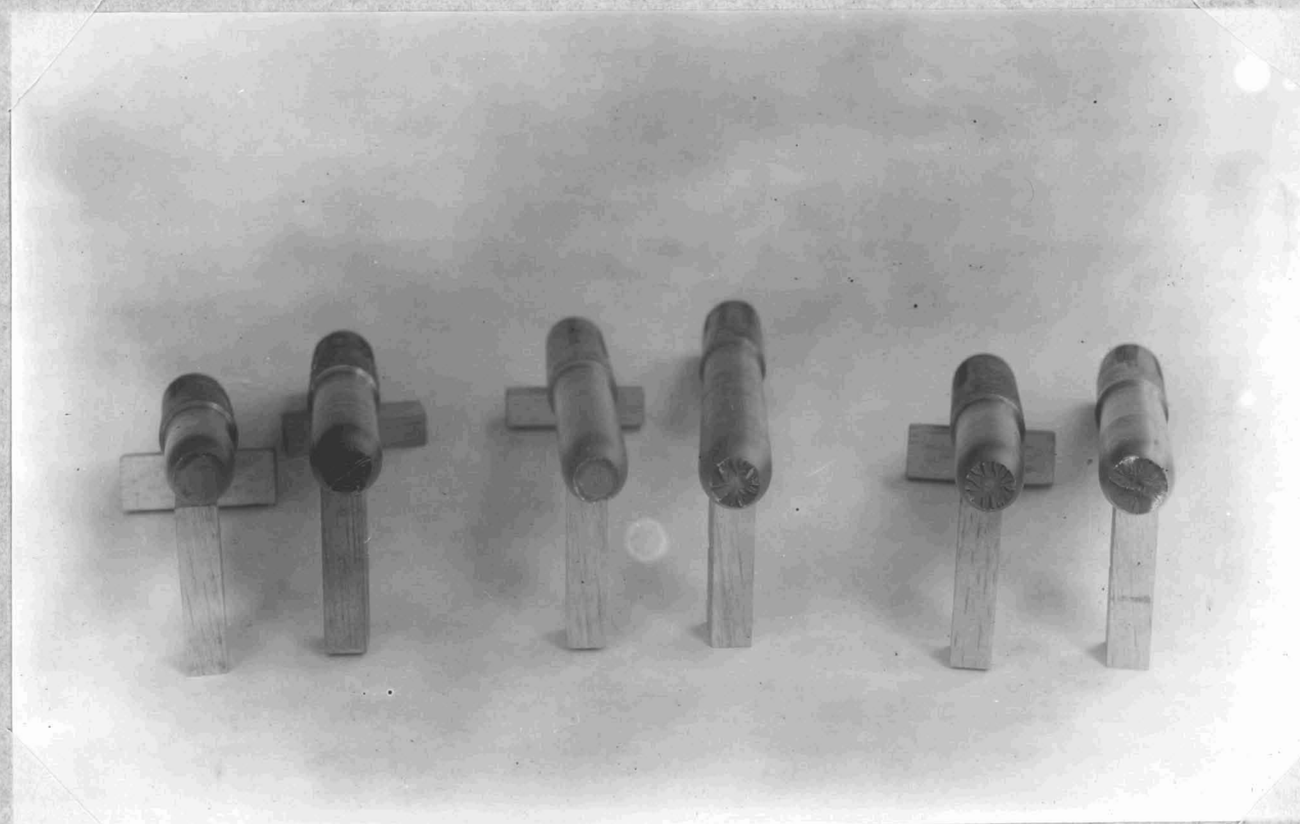

Fig. 18 - Tensile Fractures of Annealed and Quenched Alloy Steels

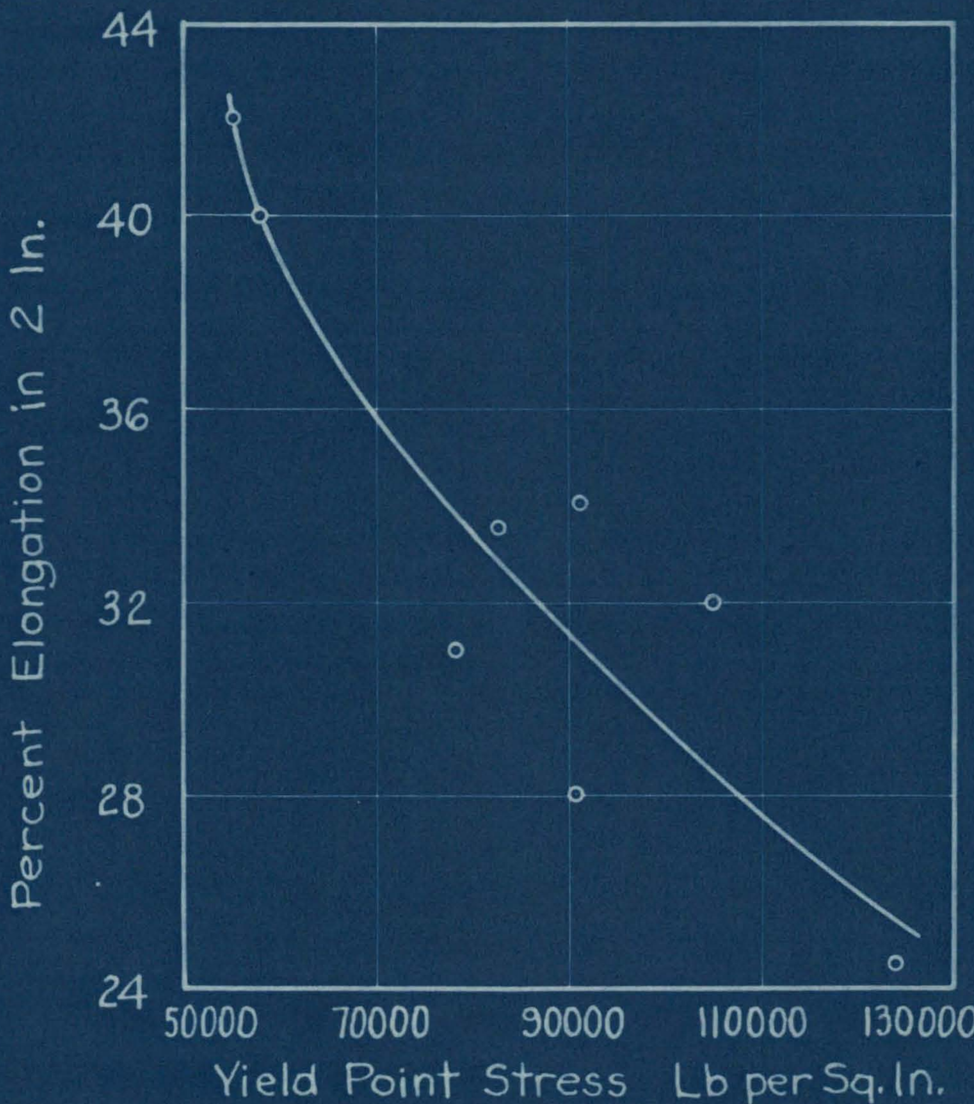

FIG 19— RELATION BETWEEN YIELD-POINT STRESS AND DUCTILITY OF QUENCHED ALLOY STEELS